Report No. CG-D-02B-93

(2)

DEVELOPMENT OF A TEST PROGRAM TO EVALUATE STRUCTURAL DEFECTS IN GLASS-REINFORCED PLASTIC (GRP)

Volume II

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FINAL REPORT
NOVEMBER 1992

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National Technical Information Service, Springfield, Virginia 22161

Prepared for:

U.S. Coast Guard
Research and Development Center
1082 Shennecossett Road
Groton, Connecticut 06340-6096

and

U.S. Department Of Transportation
United States Coast Guard
Office of Engineering, Logistics, and Development
Washington, DC 20593-0001

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Technical Report Documentation Page

1 Report No CG-D-02B-93	2 Government Accession No	3 Recipient's Catalog No
4 Title and Subtitle DEVELOPMENT OF A TEST PROGRAM TO EVALUATE STRUCTURAL DEFECTS IN GLASS-REINFORCED PLASTIC (GRP) VOLUME II		5 Report Date November 1992 6 Performing Organization Code
7 Author(s) Edward F McClave and Michael J Goodwin		8 Performing Organization Report No R&DC 16B/92
9 Performing Organization Name and Address MAR, Inc 6110 Executive Boulevard, Suite 410 Rockville, MD 20852		10 Work Unit No (TRAIS) 11 Contract or Grant No DTCG39-91-D-E33A21
12 Sponsoring Agency Name and Address U S Department of Transportation United States Coast Guard Research and Development Center Groton, CT 06340		13 Type of Report and Period Covered Final Report - December 1991 to November 1992 14 Sponsoring Agency Code
15 Supplementary Notes		

16 Abstract

A mechanical testing program was developed for evaluation of the weakening effects of different types of commonly encountered flaws on the strength of composite boat hulls A specification was developed for production of test coupons containing realistic and consistently reproducible simulated defects Tensile and flexural testing procedures were specified, including development of a technique for tensile testing of cored specimens A statistically-based test plan was developed

A mechanical testing program was conducted in which approximately 400 specimens were subjected to either tensile or flexural testing this program was conducted to verify specimen production techniques, to validate mechanical testing procedures, and to acquire information about the statistical variability of test results, which is necessary for planning future experiments

The data from the testing also supported a limited number of conclusions about the effects of defects on the strength of composite specimens of solid, balsa-cored, and plastic foam-cored construction

17 Key Words Composite Materials Tensile Testing Flexural Testing Flaw Effects	18 Distribution Statement Document is available to the U S public through the National Technical Information Service, Springfield, VA 22161

19 Security Classif (of this report) Unclassified	20 SECURITY CLASSIF (of this page) Unclassified	21 No of Pages	22 Price

Form DOT F 1700.7 (8/72) **Reproduction of form and completed page is authorized**

METRIC CONVERSION FACTORS

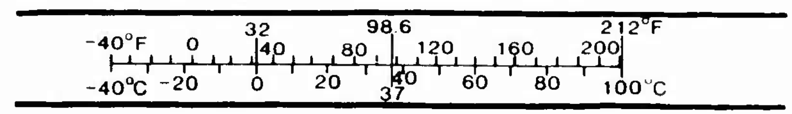
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



Preface to Volume II

This Report, titled "Development of a Test Program to Evaluate Structural Defects in Glass-Reinforced Plastic (GRP)" consists of two volumes. This volume, Volume II, contains the three principal working documents developed during the project, the Test Coupon Production Specification, the Test Procedure, and the Test Plan. Volume I contains the main body of the report and appendices relating to the production of test coupons for the pilot testing program and to results and analysis of the pilot testing program.

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ENCLOSURE 1

Test Coupon Production Specification

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Section 1

INTRODUCTION

1.1 PURPOSE

This specification has been written as part of a project to develop structural inspection standards for glass-reinforced polyester commercial vessels. The purpose of these standards is to develop a method for estimating the effects of the defects in typical boat hull panels upon the strength of the hull. The types of defects tested will include both those introduced during construction and those resulting from aging or damage while in service.

This specification details the techniques for the production of test specimens (test coupons) from various types of fiberglass reinforced polyester laminates suitable for use in testing for the effects of defects. These test specimens are intended to be produced from standard boat-building materials and by hand lay-up processes similar to those typically used in the production of glass-reinforced plastic commercial vessels.

The specifications contained herein have two primary purposes:

- To specify practical and easily reproducible techniques for producing typical defects in a range of accurately controlled sizes so that the mechanical properties of the defective test specimens accurately represent those of sections of actual hulls containing similar real defects.

- To specify production standards for test specimens that eliminate or minimize variations in factors other than those varied intentionally as a part of the experiment, which might affect the mechanical properties of the test specimens.

1.2 BACKGROUND

This project follows a project described in U.S. Coast Guard Report CG-D-02-91 in which techniques for identifying the sizes and types of defects in glass/polyester laminate structures using various nondestructive test methods were evaluated. Test panels for that investigation incorporated a number of intentionally introduced defects of various types and sizes.

The test specimens to be produced under this specification include the same types of defects used in the earlier study; however, the techniques used to introduce those defects into the test specimens differ in this specification since the testing will be for mechanical properties rather than for identification and characterization purposes.

Several of the defect production techniques used in that previous study involved removing a section of sound laminate and replacing it with a glued-in defect structure or placing a foreign structure into a curing laminate while cutting away some of the existing reinforcement in order to avoid creating a bulge. Since those tests were for purposes of detection and identification of defects, these were acceptable techniques.

However, in actual hand layup of boat hulls, defects that are introduced inadvertently during the lay-up process displace but do not interrupt the fiber reinforcement layers. When testing for the effects of defects on mechanical properties, both the displacement caused by the defect and the continuity of glass fibers are significant factors. These characteristics must be duplicated when controlled, intentional defects are introduced into laminates for testing purposes.

1.3 APPLICABLE DOCUMENTS

The documents listed in the paragraphs below are included by reference and form a part of this specification to the extent specified herein.

1.3.1 U.S COAST GUARD DOCUMENTATION.

U.S. Coast Guard Report CG-D-02-91. *Nondestructive Evaluation (NDE) of Fiberglass Marine Structures: State-of-the-Art Review* by Yoseph Bar-Cohen, Douglas Aircraft Company, McDonnell Douglas Corp., Long Beach, California, 1990.

1.3.2 AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM) STANDARDS.

ASTM Standards contained in *Annual Book of ASTM Standards*, by the American Society for Testing and Materials.

ASTM C 274-68 (Reapproved 1988). *Standard Definitions of Terms Relating to Structural Sandwich Constructions*, Vol. 15.03, 1990.

ASTM C 393-62 (Reapproved 1988). *Standard Test Methods for Flexural Properties of Flat Sandwich Constructions*, Vol. 15.03, 1990.

ASTM D 123-90a. *Standard Terminology Relating to Textiles*, Vol. 07.01, 1990.

ASTM D 618-61 (Reapproved 1981). *Standard Methods of Conditioning Plastics and Electrical Insulating Materials for Testing*, Vol. 08.01, 1990.

ASTM D 790-90. *Standard Test Method for Flexural Properties of Fiber-Resin Composites*, Vol. 08.01, 1991.

ASTM D 3039-76 (Reapproved 1989). *Standard Test Method for Tensile Properties of Fiber-Resin Composites*, Vol. 15.03, 1990.

ASTM D 3878-87. *Standard Terminology of High-Modulus Reinforcing Fibers and Their Composites*, Vol. 15.03, 1990.

ASTM D 4029-89. *Standard Specification for Finished Woven Glass Fabrics*, Vol. 07.02, 1990.

ASTM D 4357-85. *Standard Specification for Plastic Laminates Made from Woven-Roving and Woven-Yarn Glass Fabrics*, Vol. 08.03, 1990.

ASTM D 4389-89. *Standard Specifications for Finished Glass Fabrics Woven from Rovings*, Vol. 07.02, 1990.

ASTM C 4802-88. *Standard Specification for Poly (Methyl Methacrylate) Acrylic Plastic Sheet*, Vol. 08.03, 1990.

ASTM D 4850-89a. *Standard Terminology Relating to Fabric*, Vol. 07.02, 1990.

ASTM E 6-83. *Standard Definitions of Terms Relating to Methods of Mechanical Testing*, Vol. 03.01, 1990.

ASTM E 41-86. *Standard definitions of Terms Relating to Conditioning*, Vol. 08.03, 1990.

ASTM E 1325-90. *Standard Terminology Relating to Design of Experiments*, Vol. 09.01, 1990.

1.3.3 MILITARY SPECIFICATIONS.

MIL-C-9084C *Cloth, Glass, Finished, for Resin Laminates.*

MIL-C-19663 *Cloth, Woven Roving, for Plastic Laminates.*

MIL-R-21607D *Resin, Polyester, Low Pressure Laminating, Fire Retardant.*

Section 2

MATERIAL SPECIFICATIONS

2.1 DEFINITIONS - REINFORCING MATERIALS

- **Fiberglass Cloth.** A relatively light, woven material produced from twisted fiber bundles called yarns. Fiberglass Cloth contains equal amounts of reinforcement in the warp (0°) and fill (90°) directions or slightly more reinforcement in the warp than in the fill direction Its weight is specified in ounces per square yard, and it is sold by the square yard.

- **Fiberglass Woven Roving.** A relatively heavy, woven material produced from untwisted bundles of fibers called rovings. Generally, Fiberglass Woven Roving contains slightly more reinforcement in the warp than in the fill direction. Its weight is specified in ounces per square yard, and it is sold by the pound.

- **Fiberglass Mat.** A 2-dimensional nonwoven material produced either from continuous long fibers (continuous-strand mat) or from chopped fibers (the more commonly used chopped-strand mat). Fiberglass Mat consists of randomly oriented fibers bound together by a polyester resin binder and having mechanical properties approximately equal in all horizontal directions. Its weight is specified in ounces per square foot, and it is sold by the pound.

- **Biaxial Mat/Roving.** This is a nonwoven material that consists of two layers of nonwoven rovings having +45° and -45° orientations stitched to one layer of fiberglass Mat. Roving and Mat weights are specified separately in the four-digit material Type number. The first two digits specify the Roving weight in ounces per square yard and the last two digits specify Mat weight in ounces per square foot. This material is sold by the pound.

2.2 MATERIALS

2.2.1 GENERAL SPECIFICATIONS.

- All fiberglass reinforcement materials that are used must be finished with suitable sizings (chrome or silane type) for hand layup with room-temperature curing polyester resin.

- All Fiberglass Mat must have polyester resin compatible binders.

- All core materials must be of the contoured (also referred to as scored, segmented, or diced) type to replicate the core materials commonly used for vessel hulls built in female molds.

2.2.2 SPECIFICATIONS: FIBER REINFORCEMENT MATERIALS.

- Fiberglass Cloth, 10 oz nominal weight, 38" wide, E-glass, plain weave, conforming to Style No. 1800 (9.65 oz/yd^2) or Style No. 7500 (9.55 oz/yd^2) of ASTM D 4029-89 and meeting or exceeding the requirements of MIL-C-9084C.

- Fiberglass Woven Roving, 24 oz nominal weight, 38" wide, E-glass, conforming to Type 3 (24.5 oz/yd^2) of ASTM D-4389 and meeting or exceeding the requirements of MIL-C-19663.

- Fiberglass Mat, 1.5 oz (nominal weight), 38" wide, E-glass.

- Fiberglass Mat, 0.75 oz (nominal weight), 38" wide, E-glass.

- Fiberglass Biaxial Mat/Roving Type 1708 or equivalent, 38" wide, E-glass, consisting of two layers of Unwoven Roving, totalling 17 oz (nominal weight) and one layer 0.75 oz (nominal weight) Mat.

2.2.3 SPECIFICATIONS: RESIN MATRIX COMPONENTS.

- **Unsaturated Polyester Resin.** Unwaxed, fire retardant, suitable for low-pressure hand layup, containing suitable accelerators and/or promoters for room-temperature cure. Must meet or exceed the requirements of MIL-R-21607D. (Cargill Corp. 85-8533 or equivalent).
- **Initiator (Catalyst or hardener).** Methyl Ethyl Ketone (MEK) peroxide, 9% active oxygen with reduced level of hydrogen. Formulated for room-temperature accelerated/promoted polyester laminating resin in thick section layups (Pennwalt Corp. Lupersol DHD-9, NORAC MEKP-9H or equivalent).

2.2.4 SPECIFICATIONS: CORE MATERIALS.

- BALTEK Corp. Balsa core 1/2" thick, contoured, or equivalent end-grain balsa core.

- DIAB-Barracuda Corp. DIVINYCELL™ 1/2" thick PVC foam core #H80, contoured, resin coated 5 lb/ft^3.

- AIREX AG AIREX™ 1/2" thick PVC foam core #R63.80, contoured.

2.2.5 SPECIFICATIONS: CORE REINFORCEMENT MATERIAL.

- Where core reinforcement is necessary to prevent crushing under grips during tensile testing, that reinforcement shall be cut from sheets 1/2" thick Acrylic (Rohm & Haas Plexiglas™, DuPont Lucite™, or equivalent) that meet or exceed the requirements of ASTM D 4802-88.

Section 3

CHARACTERISTICS OF LAYUP

Test specimens shall be cut from flat simulated fiberglass-reinforced polyester hull panels produced by standard contact laminating techniques. Some of the specimens will contain intentionally and artificially introduced defects that have sizes ranging from the specimen thickness to multiples of the specimen thickness.

3.1 QUALITY AND UNIFORMITY OF LAYUP

Certain factors that establish the local quality of the layup (including, but not limited, to the glass/resin ratio and the presence and distribution of small unintentional defects, voids, and bubbles having sizes on the order of fractions of the laminate thickness) may interact with the effects that the large, intentionally introduced defects have upon the mechanical properties of the laminate. Therefore, no attempt should be made to produce a laminate of substantially higher local quality than that which would be typical of a normal boat hull.

On the other hand, the experiments will compare the properties of both flawed and unflawed test specimens cut from various sections of individual laminate panels and, in some cases, from different panels. In order to eliminate variations in mechanical properties between panels and between the center, end, and edge regions of a given panel, great care should be taken during the lay-up process to ensure uniformity of laminate quality throughout panels and between different panels.

In order to insure uniformity, all panels produced for test specimen shall be manufactured with no secondary bonding between lamina. For solid panels, this means that the layup must progress continuously to insure primary bonding throughout the section. For cored panels, each skin must be laid up as a continuous layer.

Due to the requirement for continuous layup and to the density and exotherm development characteristics of the type of resin specified, precautions must be taken to avoid excessive heat buildup at the beginning of the cure cycle when thick solid sections are laid up in a continuous process. These precautions include the specification of an MEKP initiator that results in slower exotherm development in thick section polyester layups and a layup and initial material temperature somewhat lower than that commonly used for thin sections or for thick sections laid up in stages.

3.2 GENERAL CHARACTERISTICS OF LAYUP

Four types of simulated hull panels shall be produced: a solid layup nominally 1/2" in total thickness and three cored layups, using 1/2" thick core material with a nominal 1/16" laminate skin on each side of the core; the cored layups are identical to one another except for the core material.

All lay-up stacking sequences are to be symmetric as defined in 1.1.2 of ASTM D-3039-76. The laminate stacking sequence below the centerplane of the laminate is to be the mirror image of that above the centerplane.

3.3 LAYUP SCHEDULE FOR SOLID TEST SPECIMENS

Figure 6-1 in Section 6 shows the lay-up schedule for the solid layup. Solid test specimens shall have the following laminate stacking sequence:

1 layer	10 oz Fiberglass Cloth
1 layer	Type 1708 Biaxial Mat/Roving (mat side facing cloth)
1 layer	.75 oz Fiberglass Mat
1 layer	24 oz Woven Roving
1 layer	.75 oz Fiberglass Mat
6 layers	24 oz Woven Roving with 1.5 oz Fiberglass Mat (5 layers total) between Roving layers
1 layer	.75 oz Fiberglass Mat
1 layer	24 oz Woven Roving
1 layer	.75 oz Fiberglass Mat
1 layer	Type 1708 Biaxial Mat/Roving (mat side facing cloth)
1 layer	10 oz Fiberglass Cloth

3.4 LAY-UP SCHEDULE FOR CORED TEST SPECIMENS

Figure 6-2 in Section 6 shows the lay-up schedule for the cored layup. Cored test specimens shall have the following laminate stacking sequence:

1 layer	10 oz Fiberglass Cloth
1 layer	Type 1708 Biaxial Mat/Roving (mat side facing cloth)
1 layer	0.75 oz Fiberglass Mat
1/2" Core	(Balsa, AIREX™, or DIVINYCELL™)
1 layer	.75 oz Fiberglass Mat
1 layer	Type 1708 Biaxial Mat/Roving (mat side facing cloth)
1 layer	10 oz Fiberglass Cloth

3.4.1 CORE REINFORCEMENT FOR CORED TENSILE TEST SPECIMENS. Cored specimens to be used for tensile testing must be reinforced under the grip area to prevent crushing under the grip pressure of the tensile test machine. During layup, sections of 1/2" thick Acrylic sheet shall be substituted for the core material under the grip area. The dimensions of the required core reinforcements are shown in **Figure 6-3** in Section 6. **Figure 6-17** is a cutting and placement guide for the core filler material.

Section 4

CONTROL OVER LAMINATE PROPERTIES

In order to eliminate sources of variation in the mechanical properties of the laminate, a number of precautions and quality control measures which exceed those generally used in boat hull construction shall be taken.

4.1 BATCH CONTROL

All materials used to produce specimens of a given test group, that is, those whose properties are to be compared directly with one another, shall be produced with resin and initiator from the same container. If possible, all test groups shall be produced with resin and initiator from the same container. If this is not possible, resin and initiator from the same manufacturer's batch shall be used and care should be taken to ensure that all individual containers are stored under similar conditions.

All specimens of a given test group shall be produced with reinforcement from the same roll, and, where multiple rolls must be used for different groups, materials from the same manufacturer's batch shall be used.

For the purposes of this specification, all the test specimens for a given type of test (tensile or flexural)that have a given core type shall be considered a group.

4.1.1 AGE OF MATERIALS

No resin or initiator shall be used if the shelf life specified by the manufacturer has been exceeded.

4.2 ENVIRONMENTAL CONTROL

Finished laminate properties depend strongly upon the initial temperature of the materials when the lay-up process commences, the ambient temperature and relative humidity during layup, the temperature and imposed pressure during the cure period (24 hours after layup), and the time-temperature history of the finished laminate in the period between the cure and the time of testing.

Temperature control of lay-up areas by use of heating devices that exhaust combustion products directly into the heated space is not acceptable since the moisture present in the combustion products makes control of relative humidity during layup difficult.

4.2.1 STORAGE OF RAW MATERIALS. Resin drums shall be stored sealed in a cool place at 40°-65°F to retard aging of the resin. The withdrawal of resin from the drums for lay-up use shall be accomplished expeditiously to avoid entry of moisture into the resin drum.

Rolls of reinforcing materials in storage shall be kept well covered to prevent dust and other contaminants from coming into contact with the reinforcement.

4.2.2 ENVIRONMENTAL CONTROL BEFORE AND DURING LAYUP. All materials to be used in the layup (resin, initiator, and reinforcement) shall be held at 70° ±15°F for at least 12 hours before and during the lay-up process.

Resin drawn from drums shall be stored in closed containers during the warm-up period before layup and, if unused, this resin shall not be returned to the drum. Open containers of resin shall not be exposed to atmospheres with a relative humidity in excess of 60% for more than 10 minutes.

Due to the high exotherm characteristics and high density of most fire-retardant resins, layup of panels, especially solid panels, the ambient temperature and resin temperature during the layup period may have to be held to a temperature less than the standard temperature of 75±5°F in order to eliminate premature gelling of the resin and excessive heat buildup in the panel. If this is found to be necessary, the ambient temperature shall be raised to the curing temperature, 75° ±5°F, as soon as the layup is finished. The relative humidity during the layup period shall not exceed 60%

4.2.3 ENVIRONMENTAL CONTROL DURING CURE. During the cure period (24 hours following layup), the temperature shall be held to 75° ± 5°F and the relative humidity to no greater than 60%.

4.2.4 POST-CURE CONTROLS. After the cure and machining of the test coupons, they shall be sealed in heavy plastic bags in a dry atmosphere as close as possible to that specified in ASTM D 618-61 for pre-test conditioning of test specimens. Subsequently, all test coupons shall be stored and shipped together to ensure similar time-temperature histories between layup and testing.

Care shall be taken to store all completed test coupons in such a manner that no stresses are placed on them, since stress during the post-cure period can effect the results of subsequent mechanical testing. In order to accomplish this, all of the specimens for a particular experiment (which will be sealed together in one bag) shall be stacked flatwise next to each other and taped together in one or more units. After sealing these units in the plastic bags, the units shall be carefully stored so that individual specimens rest on their edges to avoid any possibly of long-term bending loads.

4.3 CATALYST/RESIN RATIO

The catalyst/resin ratio shall be consistently kept in the range of 0.9% to 1.1% (.009 to .010) by weight. The catalyst ratio may be controlled by either by weighing resin and catalyst prior to mixing or by volume measurement. In order to achieve such tight tolerances on catalyst ratio by volume measurement, both the resin and the catalyst must be measured with care and with accurately calibrated and precisely graduated measuring containers.

If the volume measurement method is to be used, the densities of both resin and catalyst must either be known from manufacturer's data or they must be measured. Resin densities are typically reported in lbs. per gallon, catalyst densities are typically reported as specific gravities.

Many catalyst manufacturers provide charts which give required catalyst volumes for a given resin volume to achieve a desired catalyst ratio by weight. These are based upon standard non-fire-retardant resins (which are generally significantly less dense than the fire-retardant resin which is specified for this project) and upon standard catalyst (which is generally slightly more sense than the low-hydrogen peroxide catalyst appropriate for use with these resins), and should thus be used with caution and only after appropriate corrections are applied. Since the resin density and catalyst specific gravities, both for the actual materials and for the materials upon which the chart is based must be known to make these corrections, it is recommended that the required catalyst volume be calculated directly instead.

Calculations for catalyst volume ratios are as follows:

For the desired volume of resin, the weight is calculated:

$$W_R = V_R \cdot \rho_R$$

where: V_R is the volume of uncatalyzed resin to be measured,typically in quarts or gallons.
W_R is the weight of the resin, typically in lbs.
ρ_R is the density of the resin, typically in lbs per gallon.

The required weight of catalyst is calculated:

$$W_C = 0.011 \cdot W_R$$

where: W_C is the required weight of catalyst to catalyze a volume of uncatalyzed resin equal to V_R, providing catalyst ratio of 1% by weight of the catalyzed resin. This catalyst weight is generally converted to grams-force (453.59 g = 1 lb).

The required volume of catalyst is calculated:

$$V_C = \frac{W_C}{SG_C}$$

where: V_C is the required volume of catalyst, typically in cubic centimeters (cc).
SG_C is the specific gravity of the catalyst (grams/cc).

4.4 CONTROL OVER RESIN/GLASS RATIO

Since resin/glass ratios of the laminate tend to vary from one technician to another, with all other factors equal, all layup shall be under the direct control of *one and only one* technician during the entire test specimen production procedure.

The laminate panels shall be limited to a size that allows one person to do all the laminating without resorting to abnormally low catalyst/resin mixture ratios in order to prolong the pot life of the catalyzed resin. Accordingly, the maximum size panel to be produced shall have the width of the fiber reinforcement (38") and length corresponding to the lengths of 3 test specimens plus appropriate edge and machining allowances (approximately 78"). **Figure 6-18** shows a typical specimen layout on such a panel. There is a 2" edge allowance all around, a 3/8" transverse spacing between specimens for cutting and machining, and a 1" longitudinal spacing between specimens. This diagram corresponds with **Figure 6-17**, which shows the cutting and placement of core fillers for cored tensile specimens. If the core sections are cut 12" wide and placed as shown, the fillers will extend approximately 5.5" from each end of the specimen, as shown in **Figure 6-3**.

In order to achieve a satisfactory glass/resin ratio, grooved (aluminum or plastic) rollers shall be used for rolling out the laminate.

4.5 REINFORCEMENT DIRECTION

All reinforcement shall be positioned during layup so that the warp direction (the longitudinal direction of the material as it comes from the roll) nowhere varies by more than 5° from the direction of the longitudinal axis of the panel being produced.

Care shall be taken not to deform woven reinforcing materials during the lay-up process, in particular during defect placement, in such a manner as to cause local variations in the density or direction of the reinforcement fibers.

4.6 CURING PRESSURE

Test panels produced for evaluation of defect identification and characterization techniques as reported in USCG Report CG-D-02-91 were cured under a pressure of 0.5 lbf/ft^2, produced by a weighted top plate. During that project, reinforcement materials were cut away to allow defects to be introduced into the laminate without bulging the surface. Since this project involves mechanical testing, no interruption of reinforcement is permissible, and some of the defect types will produce bulges in the laminate which preclude the use of a top plate during curing. Therefore, no externally applied curing pressure shall be used in the production of any specimens for this project.

Section 5

INTRODUCTION OF CONTROLLED DEFECTS INTO LAMINATES

In order to evaluate the effects of certain types of defects upon the mechanical properties of fiberglass reinforced polyester laminates, test specimens which contain accurately placed, intentionally produced defects are to be fabricated. While the defect types will generally be the same ones used in the previous study reported in USCG Report CG-D-02-91, some of the defect production techniques will be considerably different for this project, as noted in Section 1 of this specification.

For the purposes of this study, all of the defect types that are normally introduced during layup of boat hulls shall be produced realistically, that is, with displacement but no interruption of the fiber reinforcement. The cracked-skin and impact damage defects are intended to simulate damage in service and do involve fiber damage.

5.1 DEFECT PLACEMENT

For uniformity, all types of intentionally introduced defects shall be placed in or under the skin of the laminate on one side only (the top as manufactured) of the test specimen, with the defect centered both longitudinally and transversely in the area of the panel from which the specimen is to be cut. The exact placement of the various defect types in the laminate stacking sequence varies and is specified as part of each individual defect production technique.

5.2 DETAILED DEFECT PRODUCTION TECHNIQUES

The techniques specified below for producing defects in layups are specified after extensive testing and comparison to determine the most effective, most easily reproduced, and least expensive methods of producing simulated defects. However, variations in the properties of wet layups due to differences in procedure between different technicians may result in slightly different results for different people, particularly for defects such as voids, uncured resin, and dry fibers.

The manufacturer of the specimens should conduct preliminary tests to verify that the defect production methods specified herein do actually produce the desired results with the particular personnel assigned to the task, and should be prepared to make minor adjustments in the details of the process if necessary.

5.2.1 VOIDS. Voids are air bubbles trapped between layers of the laminate and result from improper lay-up technique. While voids are more likely to occur when woven reinforcing material or mat fails to conform to sharp or compound curves, they can occur anywhere in a laminate structure. In cored laminates that have segmented (contoured) core materials, voids can occur adjacent to the core during cure as a result of air migrating out of the core slits.

Voids shall be introduced by inserting two circular disks of normal double-sided waxed paper into the laminate. The disk diameter shall be equal to the intended void diameter. A circular disk of soft plastic foam sponge material measuring approximately 3/8" diameter by 1/8" high shall be inserted between the waxed paper disks at their center to produce the void. A cube of foreign material of this size would normally produce a void smaller than 1" diameter if placed in the laminate alone, however, the waxed paper prevents interlaminar bonding, allowing the diameter of the waxed paper disks, rather than by the size of the sponge, to control the void diameter.

The void envelope, consisting of the two disks of waxed paper with the sponge between, can be sealed into one easily handled unit before insertion into the laminate by melting the wax of the waxed paper along the envelope edges and in contact with the sponge with a soldering iron tip or similar heating device. **Figure 6-6** shows details of the void envelope.

The voids shall be placed in the laminate between the DBM-1708 layer and the underlying .75 oz Mat layer The top waxed paper disk shall be marked so as to allow verification of defect type, size and position in the cured laminate. **Figure 6-5** shows details of the placement of the void envelope in the layup.

This technique is quite dependent upon the properties of the uncured laminate, which may vary from one layup technician to another. Therefore, the dimensions of the sponge inserted into the void may need to be varied to insure that the dislocation of the overlying laminate does not extend beyond the limits of the waxed paper disks or, on the other hand, to insure that the open area of the voids extends to near the edge of the waxed paper. If an adjustment is necessary, the thickness of the sponge (specified above as 1/8") shall be held constant while the diameter is varied to produce the desired effect.

5.2.2 UNCURED RESIN. Inclusions of uncured resin are the result of inadequate mixing of initiator into the resin before layup.

If plain uncured resin is introduced into reinforcement a layer during layup, it tends to mix with the cured resin around it, resulting in inconsistent defect sizes. Uncured resin is best simulated by a mixture of uncatalyzed polyester resin putty and colored, uncatalyzed polyester gelcoat. The putty-gelcoat mixture will be thicker than the normal resin and will have a contrasting color which will aid in identification of the defect in the finished laminate. Being more viscous than standard resin, this mixture does not migrate during layup nor does it combine readily with the normal resin in contact with it.

Once the mat layer underlying the DBM-1708 mat roving layer has been saturated with resin and rolled out, a piece of heavy paper about 4 inches square with a circular cutout of the required defect diameter is laid on the surface of the mat at the intended defect position. Using a stick or putty knife, a layer of the uncatalyzed polyester putty mixture is troweled onto the paper, and pushed through the cutout to so it sticks to the underlying resin-saturated mat. The thickness of the uncatalyzed putty should be approximately 1/16". The paper is then removed, leaving an accurately sized circular inclusion of uncured resin. Once the defects have all been positioned, the dry DBM-1708 layer is laid in place and pushed down onto the uncatalyzed putty areas so the putty permeates the downward-facing roving layers of the DBM-1708 layer. The top mat surface of the DBM-1708 layer is then wetted normally with catalyzed resin and the layup process continues . The top layer (10 oz cloth) is also wetted normally with catalyzed resin, totally enclosing the uncured resin inclusions. **Figure 6-7** shows the location of the uncured resin area in the layup.

Since the putty may have to be worked into the fabric with a putty knife, care should be taken not to disturb the surrounding laminate. The mixture ratio of uncatalyzed putty and uncatalyzed resin or gelcoat shall be determined by the layup technician in order to produce a workable mixture with a low enough viscosity to be easily incorporated into the layup, with a high enough viscosity so as not to mix readily with the surrounding catalyzed resin, and having a color distinct from that of the laminating resin.

The coloration of the uncured resin putty shall be suitable to allow easy identification of the defect type, size, and location in the finished laminate.

5.2.3 DRY FIBERS. Dry fibers result from inadequate saturation of reinforcement fibers by resin. The causes of this defect type may be careless layup or contamination of the fibers by materials that resist resin saturation.

To simulate dry fibers, a circular area of the skin shall be deprived of resin beginning with the DBM-1708 layer out to and including the 10 oz cloth top layer. The mat layer underlying the DBM-1708 layer shall be wetted out normally. A circular disk of 0.75 oz. mat, of the diameter of the desired dry area shall be placed on top of the normally wetted .75 oz mat layer underlying the DBM-1708 layer before the DBM-1708 is laid down. This will prevent the resin from in the underlying saturated mat from migrating into the intended dry area above during the layup process. **Figure 6-8** shows the location of the dry fiber area in the laminate stacking sequence.

Since some resin will migrate horizontally during layup and during the initial part of the curing period, the area initially deprived of must be slightly larger than the desired final defect size. In the cured laminate, the dry zone (defined as the zone within which the yarns of the top cloth layer can be easily moved) will be somewhat irregular. The average diameter of the dry zone shall be within $\pm 0.25"$ of the nominal defect size. (The average diameter of an irregular shape is defined as the diameter of a circle having the same area as the shape).

5.2.4 INTERLAMINAR SEPARATION. Interlaminar separation (delamination) can occur as a result of resin-poor areas of layup, contamination of reinforcement material, external damage, or poor secondary bonding due to inadequate surface preparation when a new layer of laminate is placed over an already cured layer.

Interlaminar separation shall be simulated by including a single circular disk of double-sided waxed paper in the laminate between the DBM-1708 layer and the underlying 0.75 oz. mat layer. **Figure 6-9** shows the location of the simulated delamination in the layup. The disks shall be marked so as to enable verification of defect type, size and position in the completed laminate. A felt-tip marker is a suitable marking device.

5.2.5 CRACKED SKIN. A cracked skin generally occurs when a large section of laminate is deflected by an outside force. The reinforcing fibers and the resin matrix may crack below the surface, leaving little evidence on the surface itself other than a scuff mark caused by the deflecting object.

Cracked skin shall be simulated by removing a rectangular-shaped section of the DBM-1708 layer and the underlying mat layer. This rectangle shall measure 3/16" (0.19) in the longitudinal direction of the specimen and shall be equal to the nominal defect size in the transverse direction. The cut shall completely sever all reinforcing fibers of the affected layers, and loose fiber ends in the cut shall not overlap. Any disruption of the fiber orientation caused by the cutting process shall be corrected before the top 10 oz Cloth layer is placed over the cut layer. The cut shall result in a flaw that is centered longitudinally and transversely in the test coupon. **Figure 6-11** shows a longitudinal section through the simulated crack and **Figure 6-12** shows the location and alignment of the simulated crack in the coupon. The outline of the cut shall be marked on the affected reinforcement layer in such a manner that the defect type, size, and position can be identified from the surface of the cured laminate.

5.2.6 IMPACT DAMAGE. Impact damage occurs when a small section of laminate is deflected by an impulsive force, resulting in a pattern of damage to the resin matrix and reinforcing fibers radiating out from the point of damage. Such damage is generally visible on the surface adjacent to the damage, and may be apparent on the back surface of the laminate, as well.

As close as possible to the time of testing (i.e., allowing the longest cure time possible), the specimens shall be damaged by a 3/4" spherical indentor at the energies specified by the Test Plan, using a suitable drop-weight impacting device. The specimen shall be placed a support structure similar to a flexural test jig, with roller-type supports at least 0.75" in diameter. The support span shall be 16", leaving 5" at each end beyond the support rollers. The center section shall be unsupported and sufficiently clear of support that it remains in the clear during the flexing resulting from the impact.

The specimen shall be partially restrained by loose 25 lb. weights placed on each end. **Figure 6-16** shows the setup for the impact damage procedure. This loose restraint is intended to best simulate the response of a hull panel to impact, that is, the center section acts neither as a truly cantilevered nor as a truly simply supported section, rather, its response is between these two extremes. The weights must also be restrained in such a manner that they cannot bounce toward the center section of the specimen after impact, which could cause additional damage or interfere with the catching mechanism for the drop assembly. This restraint can be accomplished with strings, elastic shock cords, or any other effective method.

The impact shall be accomplished in such a manner that the specimen is struck only once by the indentor; this requires the drop assembly to be caught on the first bounce after the impact. The weights shall be loosely restrained to prevent them falling on the unsupported span of the specimen after the impact and to prevent them from interfering with the catching of the drop assembly after the impact.

It is important that the time elapsed and the time-temperature history between layup and damage be similar for all specimens to be subjected to impact damage to ensure that damage occurs at similar levels of cure.

The maximum advisable impact energies for cored specimens using the specified impact damage setup are as follows, energies in excess of those listed may cause flexural failures of the specimen:

Airex^{TM} and Divinycell^{TM}:	30 lbf-ft
Baltek^{TM} Balsa Core	40 lbf-ft

Solid laminate specimens have been damaged at energies up to 80 lbf-ft without overall damage to the specimen.

5.2.7 EXCESSIVE CORE FILLING. Core fillings are lightweight polyester resin putties that are used to fill gaps between sections of core material and to fill the scored voids between the segments of contoured core material, which open up when the core is bent around curves.

Core-filled areas shall be created by gouging out a circular area of the core to a rounded half-ovoid shape having a maximum depth of 1/4" (half the core thickness) and filling the gouged area flush with the top of the core with the core-filling material recommended by the core material manufacturer. **Figure 6-13** shows a section through the laminate at the core-filled area.

5.2.8 FOREIGN MATERIAL INCLUSION This defect is intended to simulate the effect of dirt from a shop floor being tracked into the mold on the workers' shoes. A dirt mixture shall be prepared consisting of the following proportions by volume:

5% SAE 30 Motor Oil
5% uncured polyester resin
25% Douglas-fir Sawdust produced by a table saw with a 48-tooth blade.
30% Glass/polyester laminate granules resulting from bandsaw cutting of a section of laminate.
25% Short Milled Glass fibers
10% Potting Soil

The above mixture shall be brushed onto the mat layer underlying the DBM-1708 layer at the longitudinal center of the specimen location before the DBM-1708 layer laid down. Approximately 0.1 in^3 of this material shall be used for each 3.88 in wide specimen, and shall cover a swath on the panel extending approximately two inches each side of the longitudinal center of the specimens and covering the entire specimen width. The DBM-1708 and the overlying cloth layers shall then be laid up. The dirt shall result in an area of included dirt approximately 4 inches square at the center of each specimen after the specimens are cut from the laminate panels. **Figure 6-9** shows the position of the dirt inclusion in the stacking sequence and **Figure 6-10** shows the position of the dirt band across the coupon.

5.2.9 LAPS IN REINFORCEMENT. This characteristic is not strictly a defect since reinforcement laps are present by design even in well-made laminate structures. However, since a reinforcement lap constitutes a serious discontinuity in the reinforcing fibers, specimens having this defect will be tested to provide a realistic low-end baseline measurement for the mechanical properties of otherwise sound laminates.

Reinforcement laps shall be simulated by a lap in the type 1708 Mat/Roving layer on one side of the test specimen. The lap shall be perpendicular to the axis of the test specimen and shall be centered longitudinally on the specimen. Since methods of mating reinforcement at laps vary considerably from one layup technician to another, the customary lapping procedure of the one technician in charge of the layup shall be followed closely and consistently to produce all of the laps in reinforcement layers. **Figure 6-14** shows a longitudinal section through the lapped area and **Figure 6-15** shows the position of the lap on the coupon.

5.3 GENERAL LAYUP RECOMMENDATIONS

The specified core types and the specified acrylic core reinforcement, all of which have nominal thicknesses of 0.5", are very close in actual thickness, and any of these materials can be combined in one panel if necessary without problems.

Both core materials and core reinforcement materials should be well saturated with catalyzed resin before being placed in the layup. It is advisable that this saturation be done several minutes before placing core materials in the layup to insure that resin permeates and fills the segmentation cuts in the core materials.

The acrylic core reinforcement must be sanded before use to insure that surface gloss and residual materials from the paper covering are totally removed.

Section 6

MANUFACTURING TEST SPECIMENS FROM LAMINATE PANELS

6.1 POSITIONING OF TEST SPECIMENS IN LAMINATE PANELS

The positions of the individual test coupons in the laminate panels shall be planned according to the statistical principles of experiment design. The term experiment is used very strictly here to refer to a direct comparison in the mechanical properties of a number of individual test specimens having a systematic and intentional variation in one or more independent variables or factors (such as defect size) that are expected to affect those mechanical properties.

The positioning of the test specimens must be done in such a manner as to minimize possible sources of variation in specimen properties other than the intentionally varied factors of the experiment and to randomize variations within an experimental block that might be caused by non-random factors (biases) such as proximity to the center, edge, or end of a laminate panel (or by differences in the properties of panels, in the case of experiments involving specimens cut from more than one panel).

Accordingly, specimens that comprise an experimental block shall be taken, wherever possible, from the same general area of one laminate panel. The positions of specimens comprising an experimental block shall be randomized within this area of the panel.

6.2 EDGE ALLOWANCES

Since the test specimens produced according to this specification are intended to replicate sections of large panels and laminate properties are expected to vary near the edges and ends of individual panels, the specimens shall be positioned within the panels in such a way as to avoid the margins of the panel.

A margin of 2.25 inches at each edge and 3 inches at each end of the laminate panels shall be allowed. The margin material shall be discarded, or may be used for testing the resin/glass ratio of the panels, if this is necessary. These margins, along with appropriate cutting and machining allowances, allow 24 specimens to be cut from one 38" wide by 78" long panel.

6.3 CUTTING OF COUPONS FROM LAMINATE PANELS

Test coupons shall be cut from panels of laminate using an abrasive type circular saw blade (a Remington RemGrit™ "Grit-Edge" blade or equivalent), or a carbide-tipped toothed circular saw blade designed specifically for cutting plastic laminate, at the feed rate recommended by the blade manufacturer and with suitable vibration absorbing attachments so that as little damage as possible is done to the edges of the cut by either the cutting process itself or by the heat generated by that process.

The longitudinal axis of the coupons as they are cut from laminate panels shall vary by no more than 1° from the axis of the laminate panel.

In laying out the specimens on the panel, a machining allowance of 3/16" (.1875") shall be allowed for each cut.

6.4 ABRASIVE FINISHING OF COUPONS

After cutting the specimens from the panels (and after tab bonding for tensile coupons), the cut coupon edges shall be abrasively machined to final dimensions by a linear process (such as a belt sander) in the longitudinal direction. This abrasive machining is intended to remove all cutting imperfections which are larger than the size of the average air bubble in the resin, to insure there are no stress concentrations at the specimen edges greater than those due to normal small flaws in the laminate.

The four longitudinal edges of each coupon shall be abrasively chamfered with a uniform 45° chamfer having a width of 1/32" in order to remove any loose fibers or small matrix cracks caused by the cutting process.

The cut edges and chamfers shall be polished by hand-sanding the longitudinal direction to a uniform 220 grit surface.

6.5 COUPON SIZE TOLERANCES

The width of a finished individual test coupon shall nowhere vary by more than .05" from the nominal width specified in the Test Plan.

Coupon length shall not vary more than ±.25" from the length specified in the Test Plan.

The coupon thickness is established by the specification of laminate stacking sequence. Slight variations in actual thickness are to be expected from one area to another of individual panels, and from one panel to another. Significant variations in thickness would be expected for panels laid up by different personnel, since the glass/resin ratio, which directly affects laminate thickness for a given stacking sequence, is highly dependent upon the individual practice of the technician doing the layup.

6.6 DRAWINGS OF TEST COUPONS AND LAY-UP SCHEDULES

Figures 6-1 through **6-4** show the lay-up schedule and configuration of the test coupons. **Figures 6-3** and **6-4** show test coupons of the maximum width that can be accommodated by the testing apparatus. For certain experiments, the coupons may be produced in narrower widths.

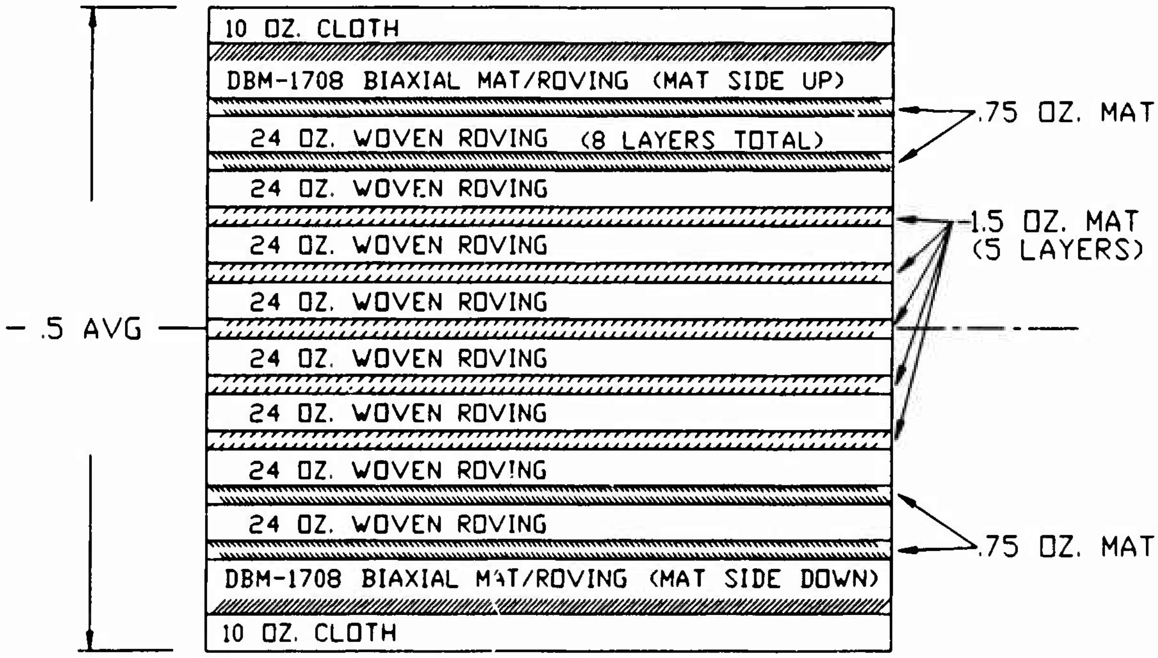

Figure 6-1. Laminate Stacking Sequence for Solid Test Coupons

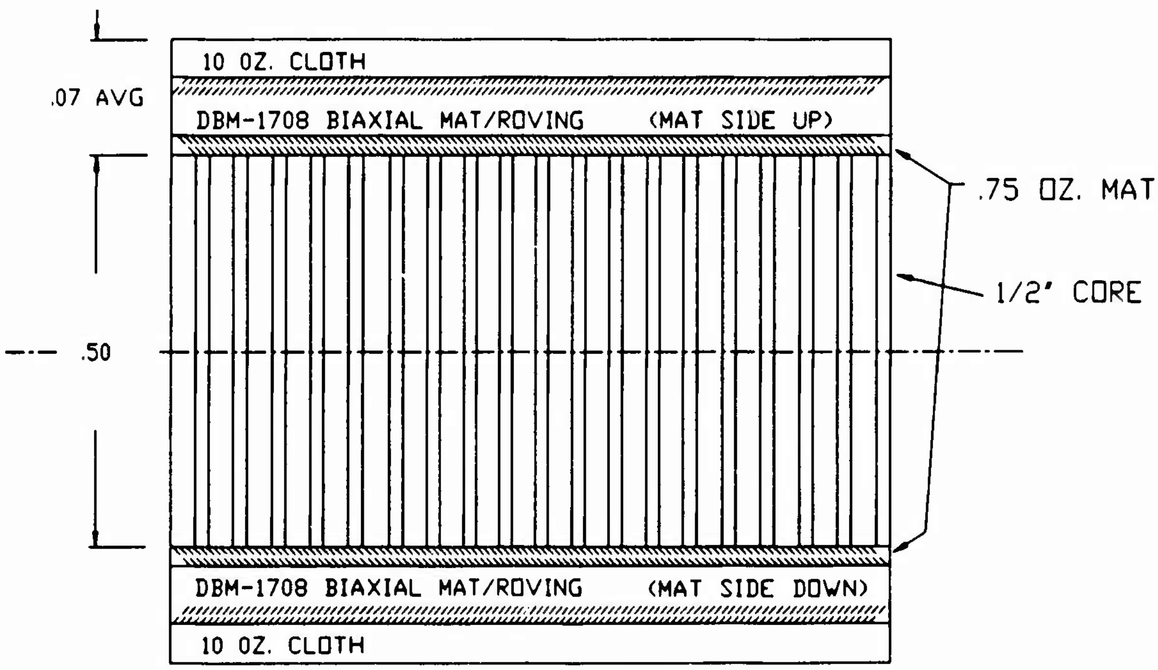

Figure 6-2. Laminate Stacking Sequence for Cored Test Coupons

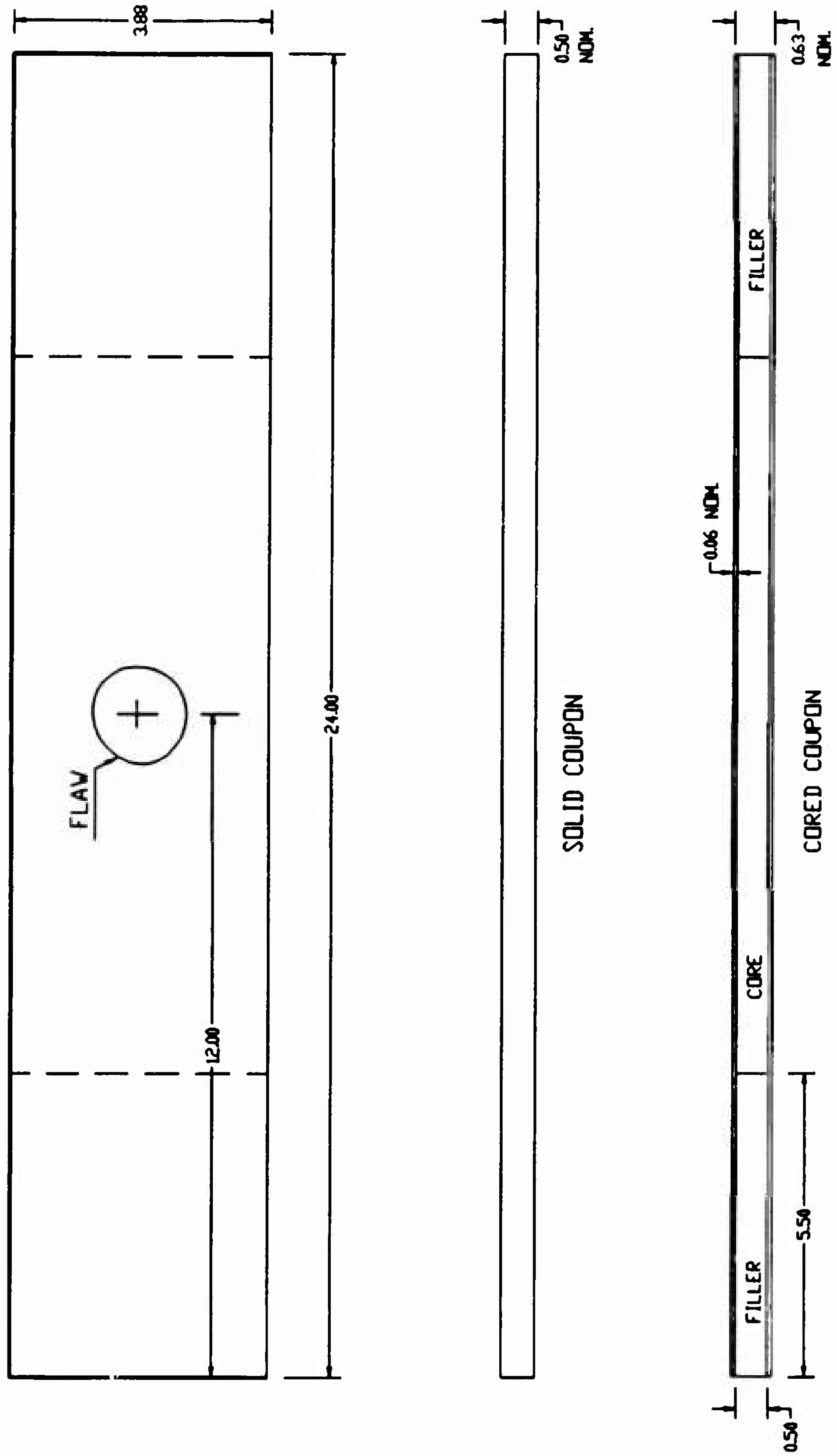

Figure 6-3. Tensile Test Coupon

138-92-4

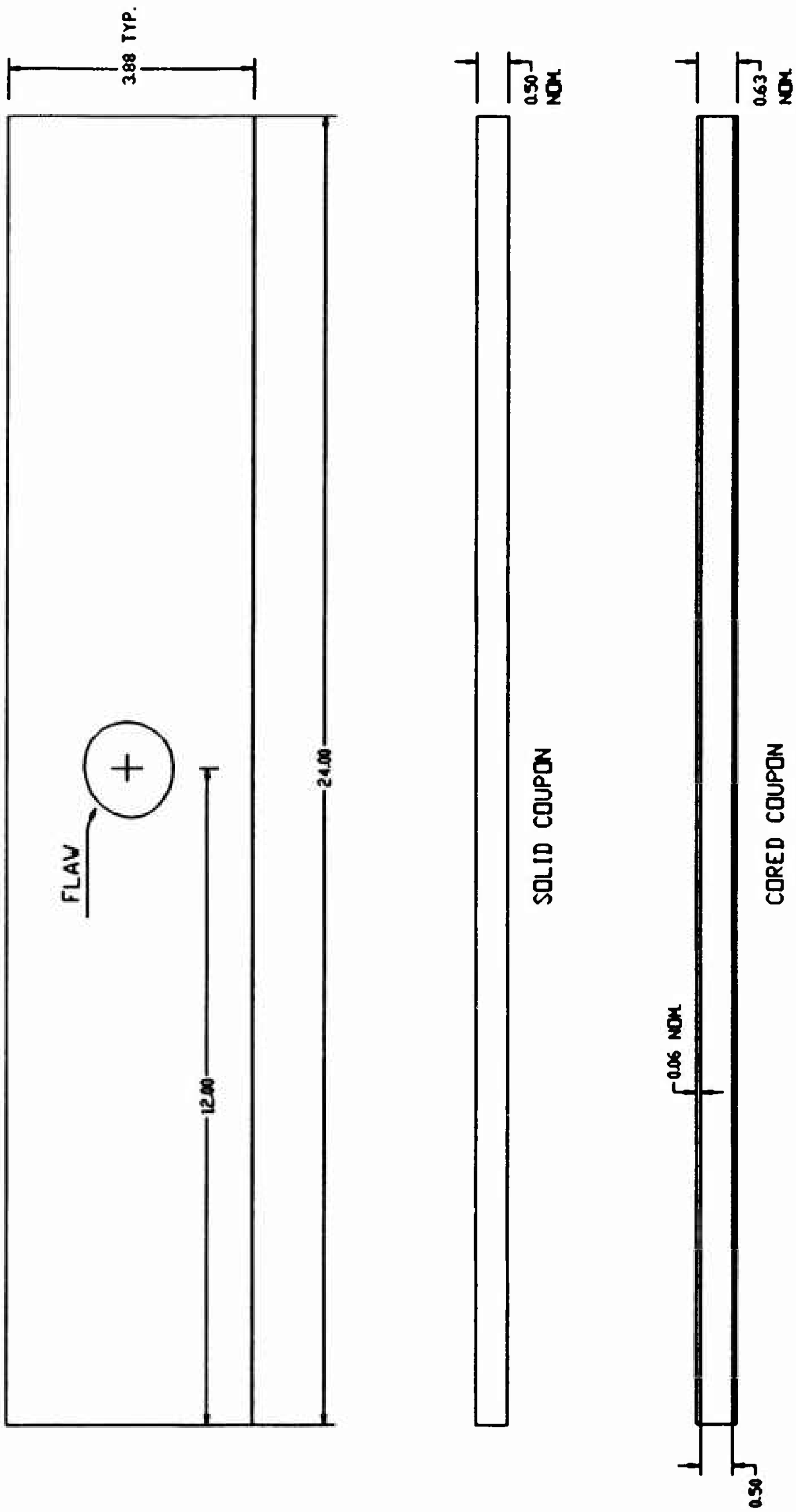

Figure 6-4. Flexural Test Coupon

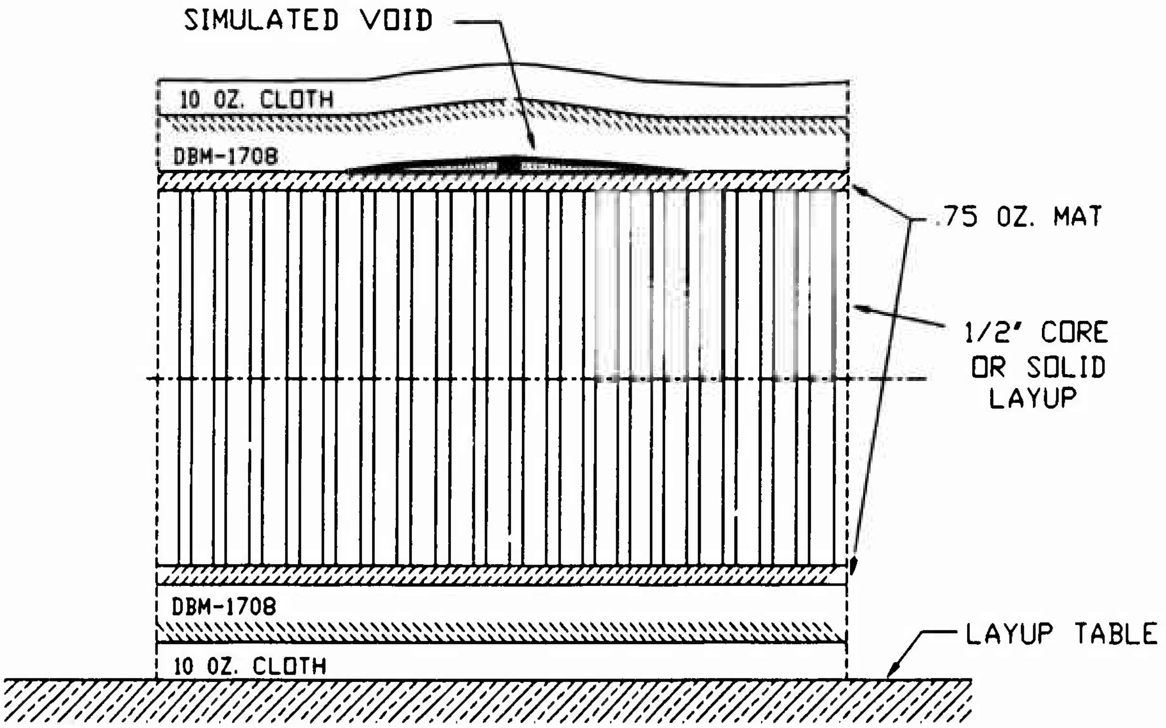

Figure 6-5. Section Through Simulated Void

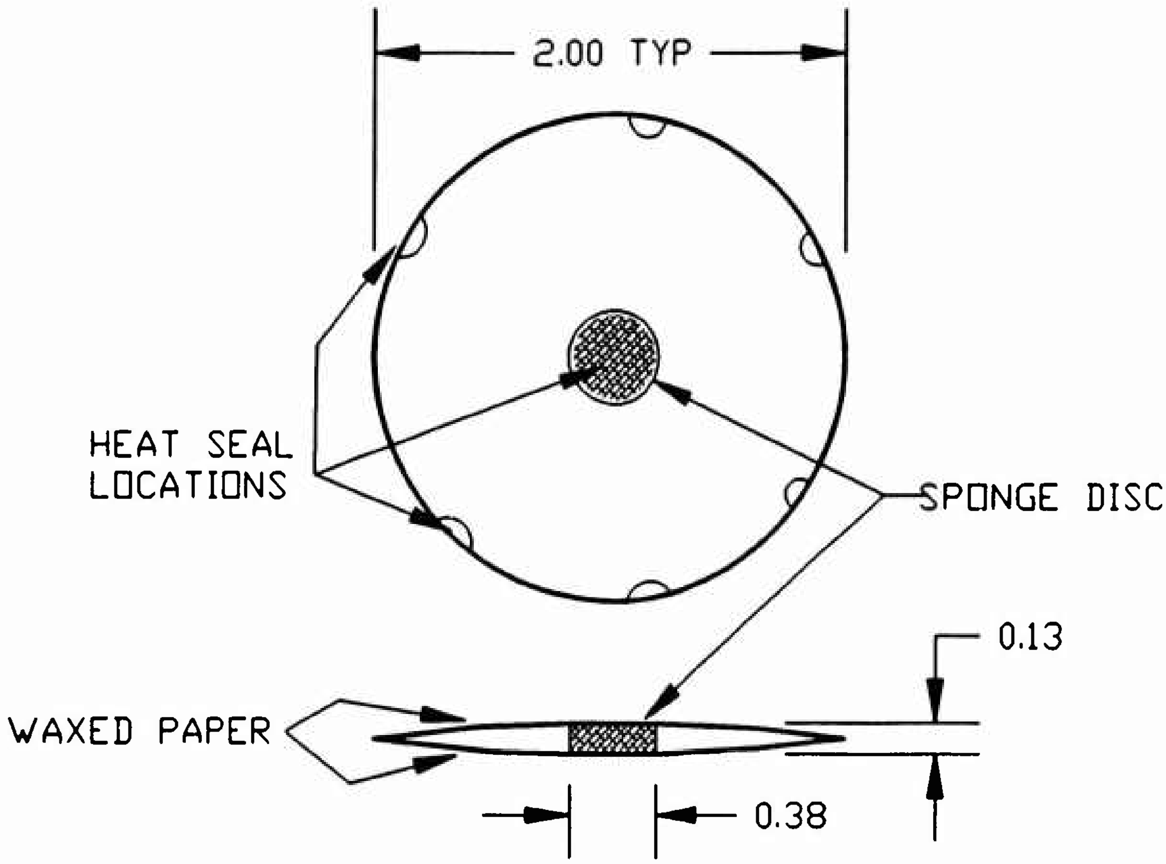

Figure 6-6. Details of Simulated Void Envelope

138-92-7

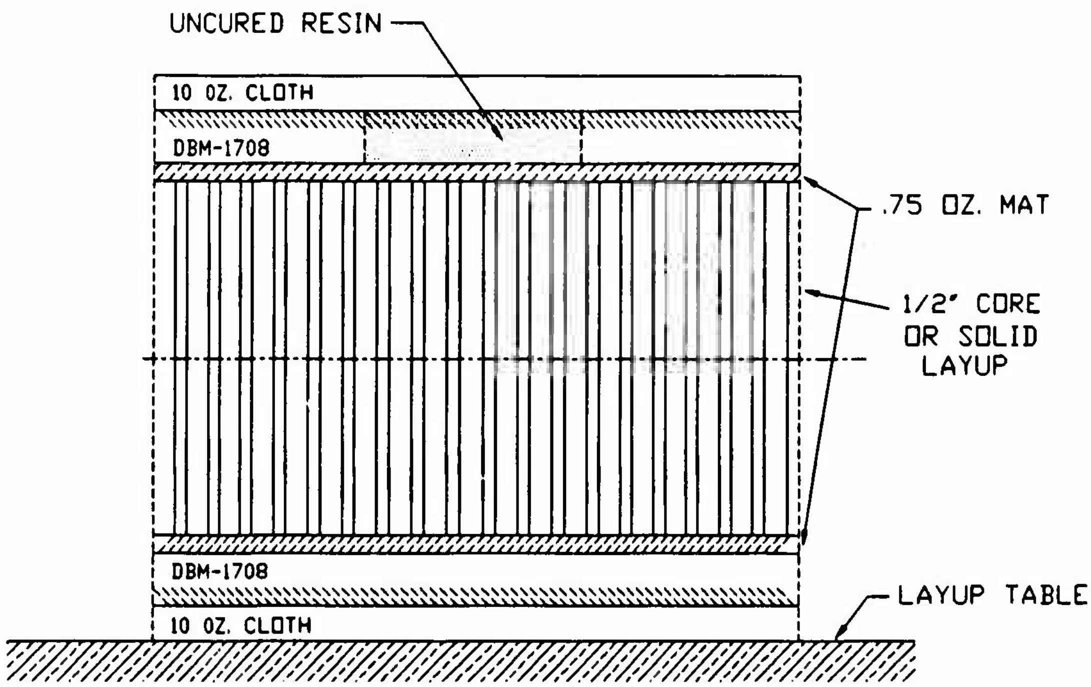

Figure 6-7. Section Through Uncured Resin Inclusion

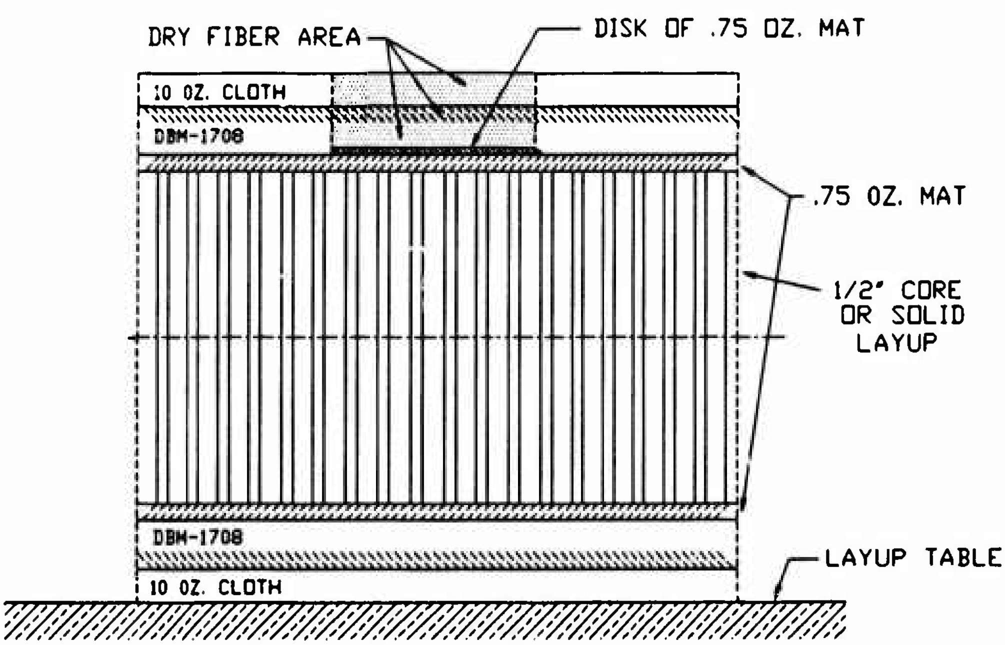

Figure 6-8. Section Through Dry Fiber Area

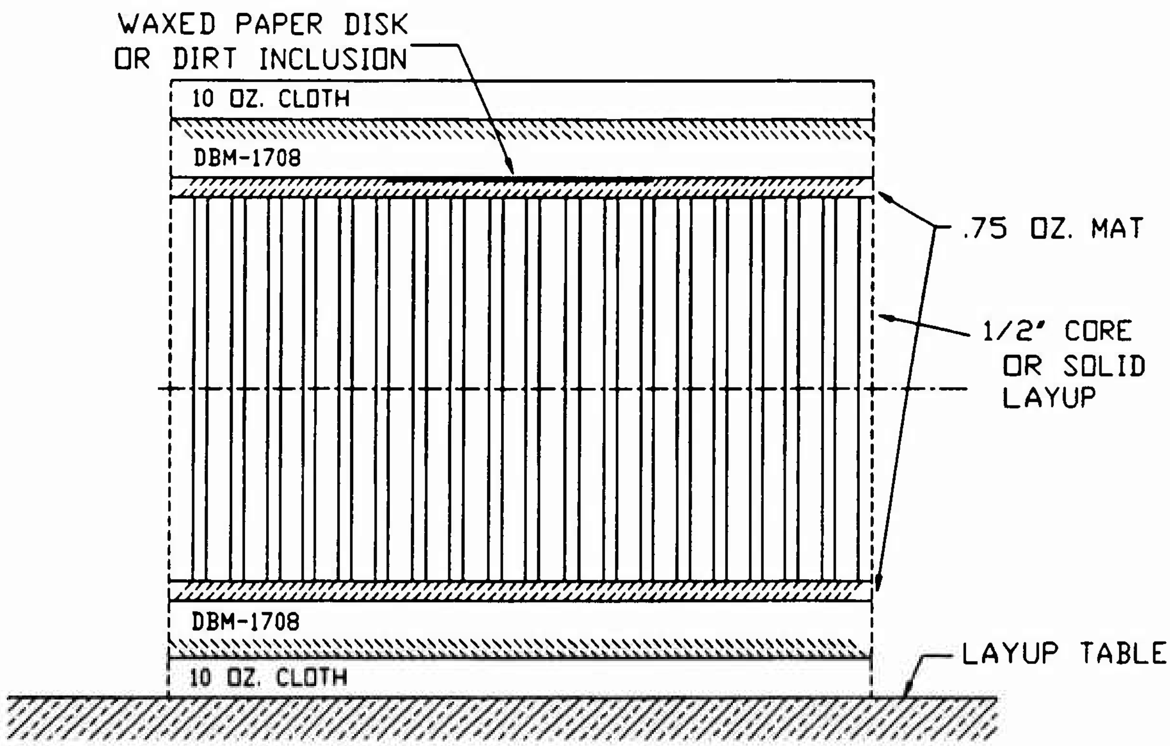

Figure 6-9. Longitudinal Section Through Delamination or Dirt Inclusion

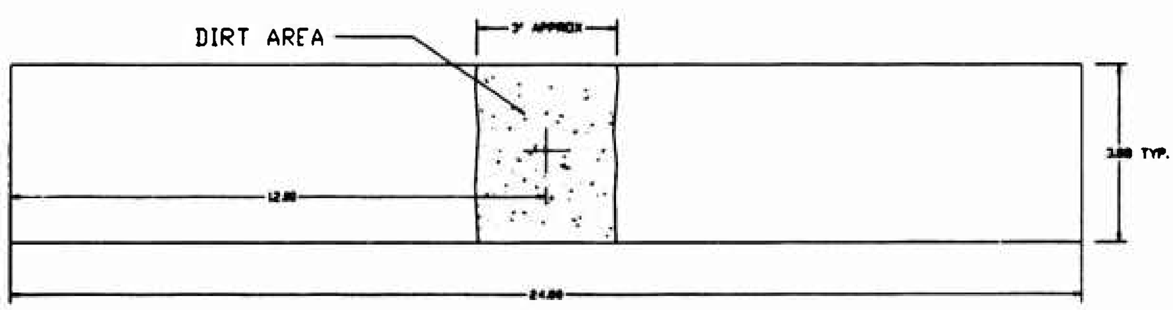

Figure 6-10. Location of Dirt Inclusion

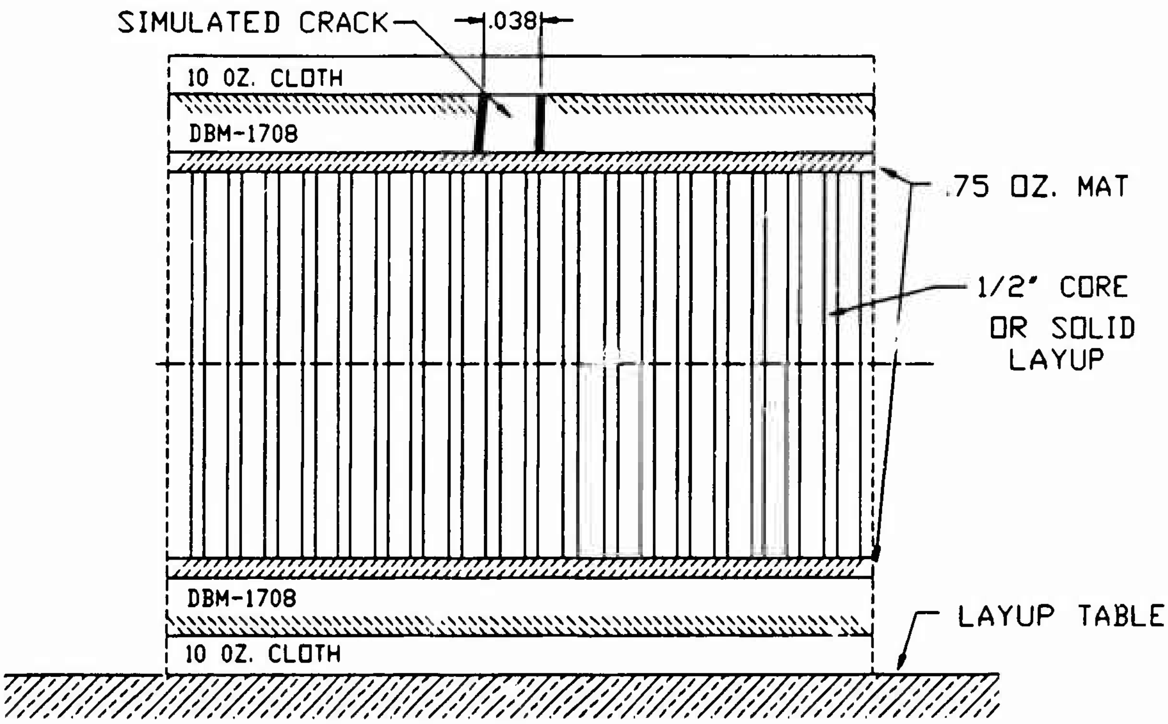

Figure 6-11. Longitudinal Section Through Simulated Crack

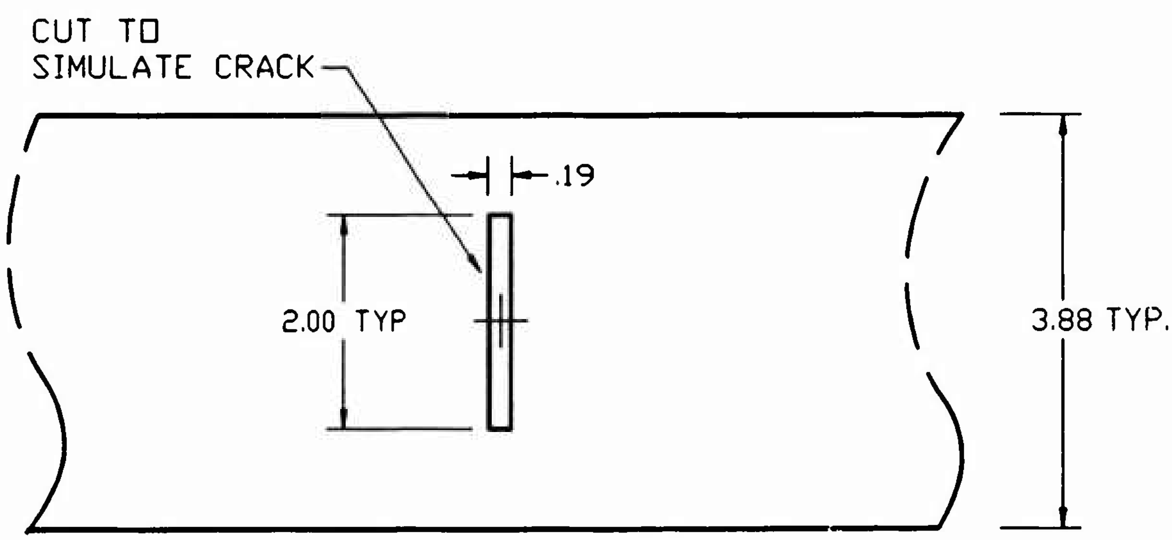

Figure 6-12. Position of Simulated Crack

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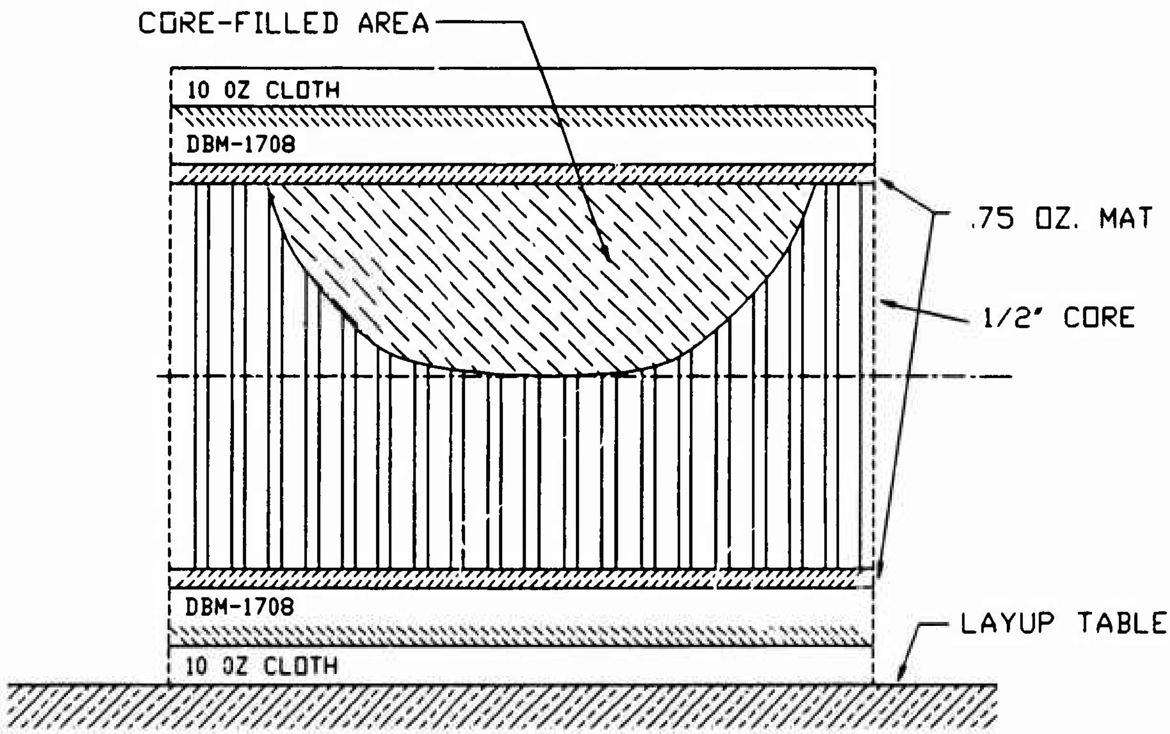

Figure 6-13. Section Through Core-Filled Area

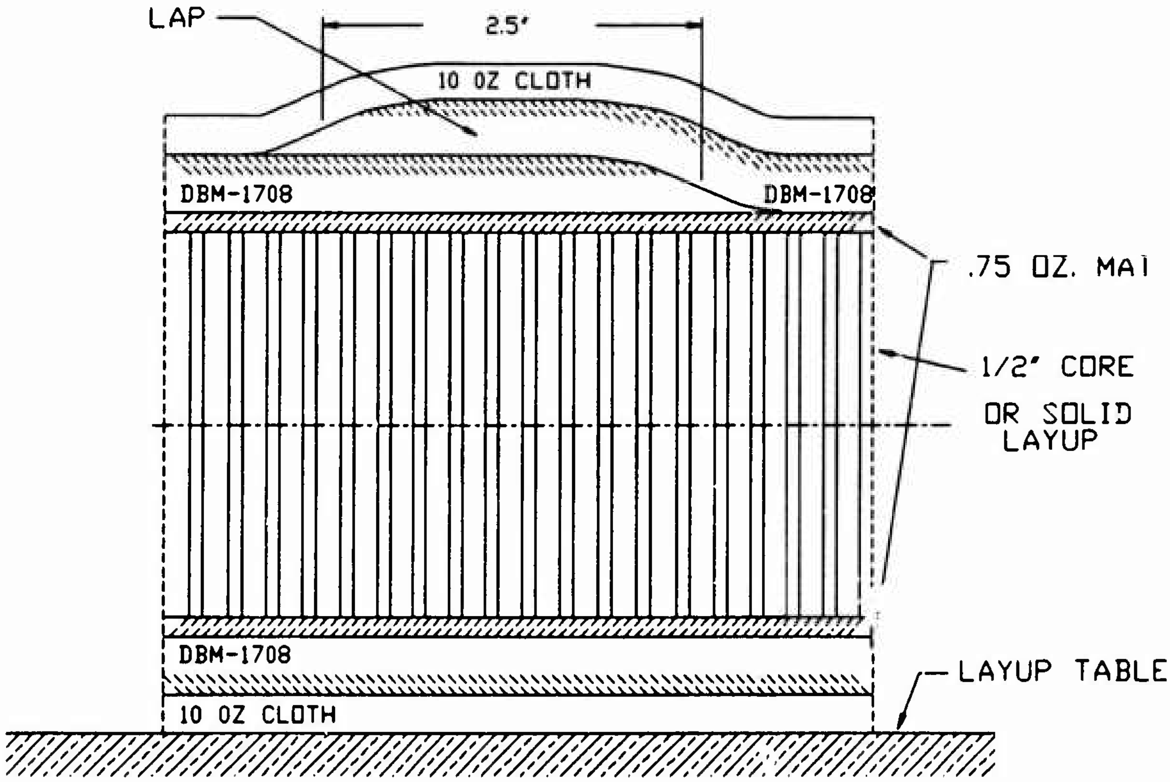

Figure 6-14. Longitudinal Section Through Lap in Reinforcement

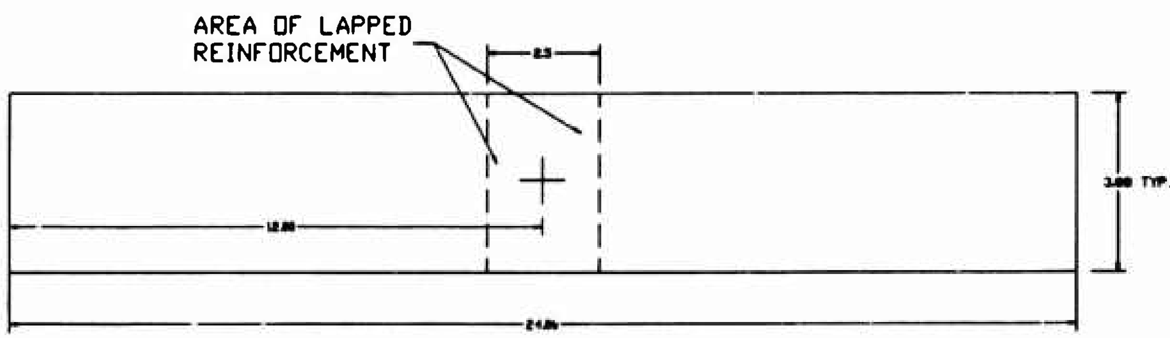

Figure 6-15. Position of Reinforcement Lap in Coupon

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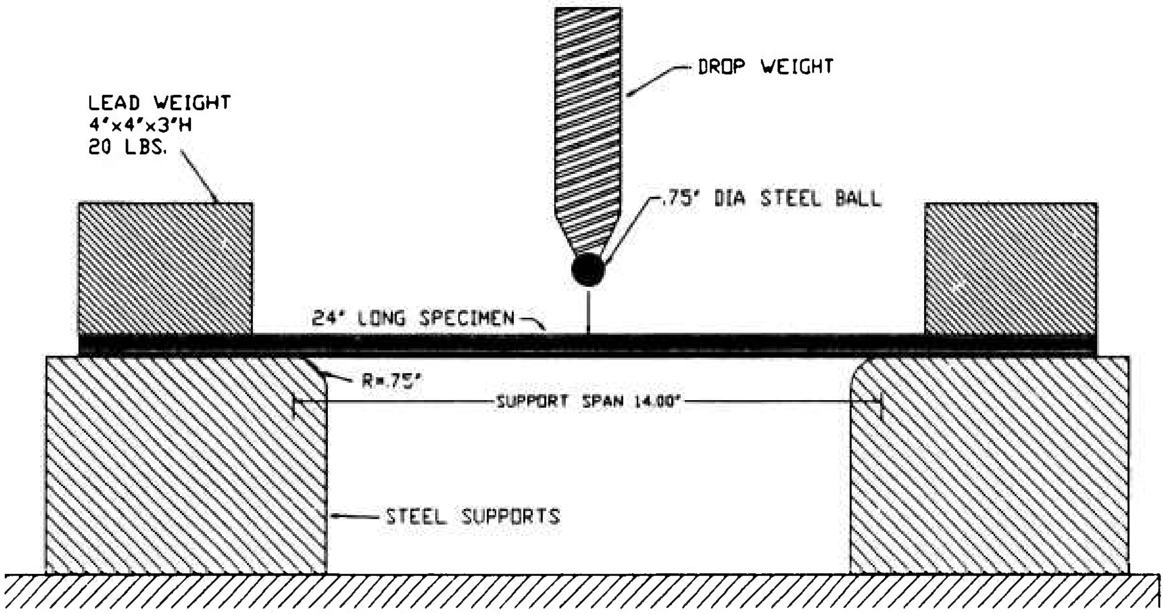
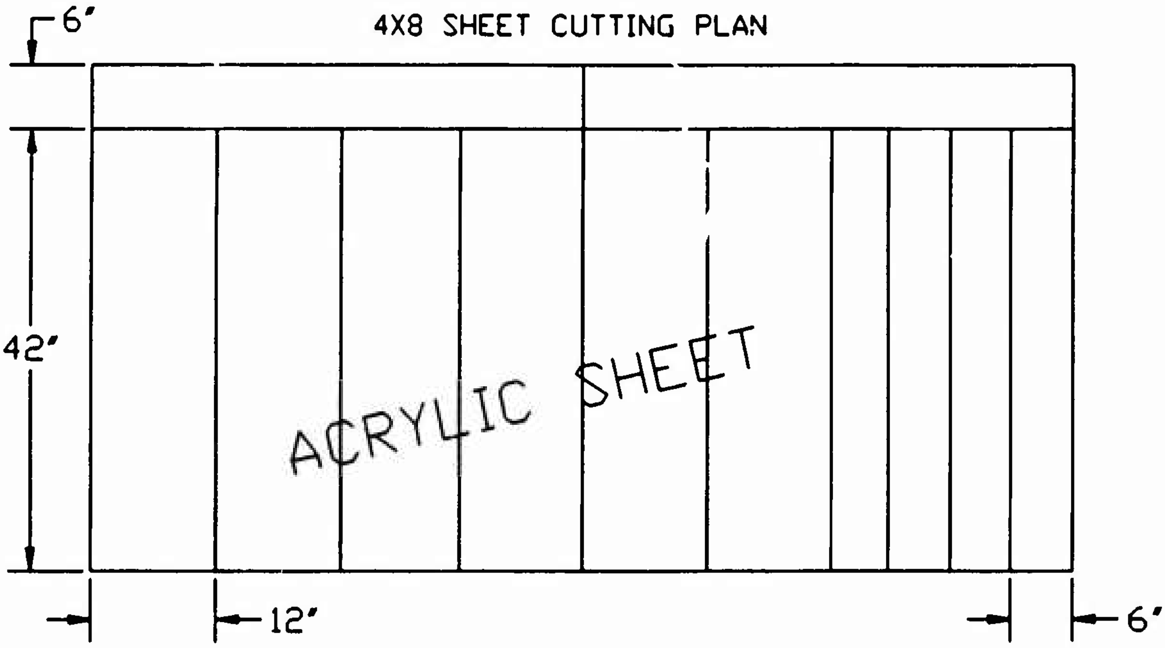


Figure 6-16. Setup for Impact Damaging of Test Coupons



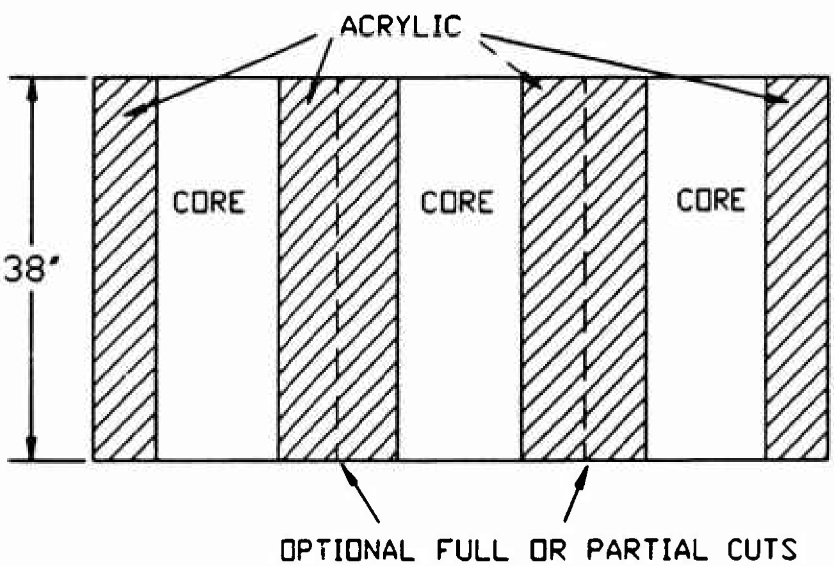


Figure 6-17. Core Fillers for Cored Tensile Specimens

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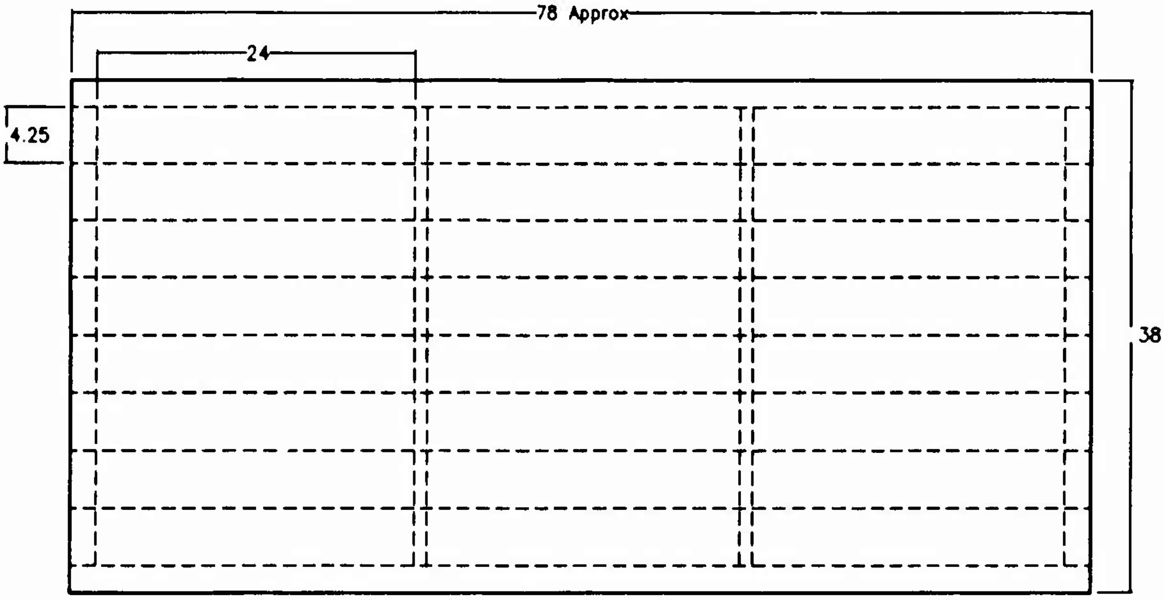

Figure 6-18. Typical Panel Layout

Section 7

QUALITY CONTROL

Inspections of the coupon production process are essential in maintaining consistent quality and consistency of the test coupons, and in insuring that proper defect configuration and placement are being maintained. In addition, it is important that the defect size, type, and specimen numbers of finished coupons be verified to insure that the experimental data obtained during testing can be correlated to the correct defect configuration.

7.1 INSPECTIONS OF FABRICATION AREAS

Supervisory personnel shall make frequent inspections of fabrication areas to insure that proper environmental conditions and an appropriate degree of cleanliness are being maintained.

7.2 INSPECTIONS OF PANELS

Supervisory personnel shall make periodic observations of the layup process to insure that the proper layup schedule and stacking sequence are being adhered to.

Panels shall be inspected after layup to verify defect size, type, and placement and to verify that the panel has cured properly.

7.3 INSPECTIONS OF FINISHED SPECIMENS

Supervisory personnel shall inspect the cut and finished specimens before delivery to the testing facility to verify the following:

- The dimensions and surface finish of the specimens
- The quality of the layup - including proper bonding of core to skin and a lack of obvious unintentional defects
- The adequacy and accuracy of specimen numbering.
- Proper defect type, configuration, size, and positioning.

ENCLOSURE 2

Test Procedure

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Section 1

INTRODUCTION

1.1 PURPOSE

The purpose of this specification is to establish effective and consistent procedures for tensile and flexural testing of specimens of solid and cored glass/polyester laminates.

1.2 OVERVIEW OF TESTING

Mechanical testing will be conducted on solid glass/polyester specimens approximately 0.5" thick and 3.875" wide and on cored sandwich construction specimens 3.875" wide and having 0.5" thick balsa or plastic foam cores with symmetrical glass/polyester skins approximately 0.09" thick (for a total thickness of approximately 0.68"). All specimens will have lengths of 24". Some of the specimens will have defects which will have been introduced intentionally during manufacture.

The tests will generally follow the procedures outlined in ASTM D 3039 for tensile testing, in ASTM D 790 for flexural testing of solid specimens, and in ASTM C 393 for flexural testing of cored (sandwich construction) specimens. However, since the specimens for this test are much larger than typical ASTM test specimens, some of the procedures and specimen proportions will be altered. The large tensile cross-sections and the stiffness of large flexural specimens introduce problems which are not encountered in the testing of smaller specimens. Tensile testing of cored specimens presents unique problems due to the necessity of replacing or reinforcing the core material to prevent crushing under the testing machine grips.

1.3 AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM) STANDARDS

ASTM Standards contained in *Annual Book of ASTM Standards*, by the American Society for Testing and Materials.

ASTM C 274-68 (Reapproved 1988). *Standard Definitions of Terms Relating to Structural Sandwich Constructions*, Vol. 15.03, 1990.

ASTM C 393-62 (Reapproved 1988). *Standard Test Methods for Flexural Properties of Flat Sandwich Constructions*, Vol. 15.03, 1990.

ASTM D 618-61 (Reapproved 1981). *Standard Methods of Conditioning Plastics and Electrical Insulating Materials for Testing*, Vol. 08.01, 1990.

ASTM D 790-90. *Standard Test Method for Flexural Properties of Fiber-Resin Composites*, Vol. 08.01, 1991.

ASTM D-2584-68 (Reapproved 1985). *Standard Test Method for Ignition Loss of Reinforced Resins*, Vol. 08.03, 1990.

ASTM D-2734-70 (Reapproved 1985). *Standard Test Methods for Void Content of Reinforced Plastics*, Vol. 08.03, 1990.

ASTM D 3039-76 (Reapproved 1989). *Standard Test Method for Tensile Properties of Fiber-Resin Composites*, Vol. 15.03, 1990.

ASTM D 3878-87. *Standard Terminology of High-Modulus Reinforcing Fibers and Their Composites*, Vol. 15.03, 1990.

ASTM E 41-86. *Standard Definitions of Terms Relating to Conditioning*. Vol. 08.03, 1990.

ASTM E 4-83a. *Standard Practices for Load Verification of Testing Machines*, Vol. 08.03, 1990.

ASTM E 6-83. *Standard Definitions of Terms Relating to Methods of Mechanical Testing*, Vol. 03.01, 1990.

ASTM E 171-82. *Standard Atmospheres for Conditioning and Testing Materials*, Vol. 08.03 1990.

Section 2

PRE-TEST PREPARATION OF TEST SPECIMENS

Since the mechanical properties of glass/polyester laminates, especially those which have cores, depend upon the temperature and moisture content of the material, specimens must be conditioned before testing to insure that the specimens have uniform temperatures and moisture contents.

2.1 UNIFORM TREATMENT OF TEST GROUPS

The specimens to be used in these tests are considerably larger than usual ASTM mechanical test specimens. While the time required for specimens to come to temperature equilibrium in a conditioning environment is relatively short, fairly long time periods might be required for specimens having moisture contents which differ significantly from the equilibrium moisture content in the test room to reach an equilibrium moisture content during conditioning. In addition, due to the large number of specimens and their large size, the space required for complete conditioning to moisture content equilibrium might be excessive.

As a result, some specimens might be tested before they have reached full equilibrium with the test room environment. These specifications will stipulate guidelines to insure that the specimens which constitute an individual experiment will be tested at similar moisture contents even if they cannot be conditioned for a long enough time to reach their equilibrium moisture contents in the conditioning environment.

2.2 SPECIMEN NUMBERING

Each specimen shall bear a unique identifying number, written directly on the specimen or on a permanent adhesive label affixed to the specimen in a location safe from damage by the testing apparatus and away from the expected region of failure.

2.3 CONDITIONING

2.3.1 PRE-CONDITIONING STORAGE. All specimens which constitute an individual experiment shall be wrapped and stored together before the conditioning period.

2.3.2 CONDITIONING AND TESTING OF EXPERIMENTAL GROUPS. Specimens constituting an individual experimental group shall be unwrapped and conditioned together and the entire group of specimens shall be tested within a maximum timespan of 48 hours, preferably on the same day, to insure that testing is completed under conditions of uniform moisture content and temperature.

2.3.3 SPECIMENS TO BE IMPACT DAMAGED. Specimens for impact damage experiments shall be damaged immediately before commencement of the conditioning period. This will insure that the laminate has had the maximum possible post-cure before the damage is inflicted. Specimens for a given experiment should be impact damaged during the same session to insure uniformity of cure.

2.3.4 ENVIRONMENTAL CONDITIONS FOR CONDITIONING. After removal from sealed plastic bags, specimens shall be conditioned for a minimum of 5 days immediately preceding testing at a temperature of 73° ± 4° and a relative humidity of 50% ± 5%.

2.3.5 SUPPORT DURING CONDITIONING. Specimens shall be arranged during conditioning so that there is adequate air circulation to all surfaces. Specific support schemes are suggested in section 8.1 of ASTM D 618-61.

2.3.6 TESTING ENVIRONMENT. Testing shall be conducted in an the same environmental conditions specified for conditioning.

Section 3

GENERAL TESTING REQUIREMENTS

3.1 MACHINE CALIBRATION

All testing machines used in these experiments shall have valid and current load verification certificates in accordance with ASTM E 4-83a.

3.2 SIZE CAPACITIES OF MACHINES

Both tensile and flexural testing machines shall accept specimens having a width of at least 4.0", a thickness of at least 0.88", and a total length of at least 25".

3.3 MEASUREMENT OF SPECIMEN DIMENSIONS

The width and thickness of each specimen shall be measured before testing and the average measurements shall be recorded on the specimen data sheet for that specimen as detailed in 4.4.7 and 5.3.6 of this test procedure.

Measurements shall be made of specimen width and thickness at the points indicated in **Figure 1** in Appendix B for tensile specimens and in **Figure 2** for flexural specimens. When there are obvious local surface defects at the designated measurement point that would affect the measurements, the measurement shall be taken at the closest point to the designated point that does not have local defects.

Individual measurements shall be made with a caliper or micrometer accurate to .001". The largest and smallest of the six thickness measurements for each specimen shall be disregarded; the average thickness is the arithmetic mean of the remaining four thickness measurements. The average width shall be the arithmetic mean of the three width measurements. The average thickness and width shall be reported on the specimen data sheet to the nearest .01".

3.3.1 MEASUREMENT OF CORE THICKNESS. The core thickness of each of the core types shall be determined once at the beginning of the test program. Sections of the core materials from the same lot as that used in specimen construction shall be measured.

Balsa core materials, with any fabric backing removed, shall be measured directly with a micrometer or caliper, at 5 different locations, to .001". The average of these measurements shall be reported as the core thickness.

Plastic foam core materials, with any fabric backing removed, shall be measured by placing 1/2" diameter metal disks under the anvils of the micrometer or the jaws of the caliper, taking the measurement, then subtracting the thickness of the disks. This procedure shall be done at 5 different locations on the core and the results averaged and reported as the core thickness.

3.4 COMPUTATION OF SPECIMEN CROSS-SECTIONAL AREA

For solid specimens, the cross-sectional area of laminate shall be computed as the product of the average specimen width and the average specimen thickness as defined in 3.3 of this specification.

For cored specimens, the cross-sectional area of laminate shall be computed as the average sandwich thickness minus the core material thickness (measured as specified in 3.3.1) multiplied by the average specimen width.

3.5 SPECIMEN DATA SHEETS

A specimen data sheet, following the format of the tensile and flexural data sheets presented in Appendix A, shall be prepared for each specimen tested. A computer data file is an acceptable substitute for the specimen data sheets. In either case, the data sheets or files shall be duplicated and copies stored in at least two separate locations to guard against loss of the data.

Since detailed reporting requirements differ for tensile and flexural testing, they will be specified separately in sections 4 and 5 of this specification, respectively.

3.6 TREATMENT OF BROKEN SPECIMENS

In the case of failures which cause the specimen to break into pieces, the pieces shall be fastened together securely with tape or by other suitable means. The specimen number shall written on any pieces which do not contain a legible specimen number after failure.

3.7 HANDLING OF TEST DATA

One copy of the each digital test data file shall be retained by the testing laboratory, and two identical copies of each digital data file, on separate disks, shall be delivered to the contracting organization.

One copy of each specimen data sheet, whether on disk or paper, shall be retained by the testing laboratory, and one copy if on paper or two copies if on disk shall be delivered to the contracting organization.

3.8 PHOTOGRAPHIC DOCUMENTATION OF TESTING

Photographs shall be taken of both the tensile and flexural test setups, showing clearly both the overall machine layout and all important details of the test setups, including tensile test machine grip mechanisms, and the flexural test loading and support assembly, and all measuring equipment. Any photographs which do not clearly show a specimen shall show a clearly graduated ruler or other appropriate object for scaling purposes.

In addition to detailed photographs of the test setup and laboratory layout, photographs shall be taken of the actual testing of a representative group of specimens, flawed and unflawed, tensile and flexural, exhibiting all flaw types. These photographs shall show the specimens both before and after the tests, and shall clearly indicate the methods of attachment of measurement apparatus. Photographs of flexural tests in progress shall include specimens near the point of failure to indicate the amount of deflection experienced.

All photography shall be done with 35mm color print film, using appropriate lighting to show important details. Each photograph shall be documented in a written log or a computer text file which explains the content of the photograph and noting the specimen number in the case of photographs of an actual test in progress.

Two 5x7 inch color prints of each photograph, numbered to correspond with log entries, the negatives, and the log, either on paper or on disk, shall be delivered to the contracting organization at the conclusion of the testing.

Section 4

TENSILE TESTING EQUIPMENT AND PROCEDURE

Specimens will be tested to failure on a tensile-testing machine of suitable capacity, at a constant loading rate of 0.12 in/min, with load and strain (extension) recorded automatically at specified time intervals, and with details of failure recorded manually.

4.1 EXPECTED TENSILE CHARACTERISTICS

Tensile specimens can be expected to experience very little deformation beyond the linear load-strain region before failure occurs.

The average tensile breaking strength of the glass/polyester laminate used in these tests (hand-layup, room-temperature cure, low positive curing pressures) can be expected to fall in the 30-40,000 lbf/in^2 range. Based upon this figure, a solid specimen 0.5" thick and 4" wide can be expected to fail at 60-80,000 lbf and a cored specimen 4" wide with a 1/16" thick skin on each side of the core can be expected to fail at 15-20,000 lbf.

Tensile strain at failure can be expected to fall in the 1-1.5% range, giving a total tensile deformation of 0.15 to 0.225" at failure for a specimen 24" long and 15" between grips. These figures have been verified by preliminary testing of specimens having the same characteristics as those specified for these tests. The equipment specifications contained in paragraph 4.2 are based upon these expected tensile strengths.

4.2 TENSILE TEST MACHINE REQUIREMENTS

4.2.1 ACCURACY. The tensile testing machine and its load measuring devices shall meet the requirements of 6.2.5 and 6.2.6 of ASTM 3039-76.

4.2.2 LOAD CAPACITIES. Based upon the above figures, the machine used for testing the solid tensile specimens for these tests shall have a rated capacity of no less than 100,000 lbf, and the machine used for testing the cored specimens shall have a rated capacity of no less than 50,000 lbf. Requirements for grip area specified in section 4.2.3 may increase the sizes of the machines required by this section.

4.2.3 MACHINE GRIP AREA. The area of the specimen contacted by the machine grips shall be sufficiently large that the gripping force required to load the specimen to failure without slippage shall not result in compressive stresses in excess of 5000 psi in the gripped area of the specimen.

It should be noted that the necessity of spreading the grip load over a large area may dictate the use of a machine having a larger capacity (and larger grips) than specified in paragraph 4.2.2. (4.2.2 is based solely upon the expected load required to break the specimen, with a suitable reserve capacity.)

In order to avoid stress concentrations near the inboard edges of the grips, the width of the grips shall be no less than 90% of the width of the specimens, or 3.5 in.

4.3 PRELIMINARY TESTING AND SETUP

Because of the large cross-sectional area of laminate in the specimens and the limited grip area provided by the testing machine, the minimum grip pressure required to insure against slippage may be only slightly less than that which will compressively deform the material under the grips enough to induce tensile failures in the grip area. The compressive yield strength of certain components of the laminate may be as low as 7,000 lbf/in^2.

A sufficient number of extra test specimens shall be provided to allow trial-and-error experimentation to determine the proper grip pressure, to try different grip surface patterns if these are available. Experimentation to determine the optimum grip surface pattern may allow a reduction of the required grip load, lowering the compressive stress under the grip area.

Preliminary experimentation will also provide an estimate of the time to failure for the loading rate selected. The time-to-failure estimate will be used to determine the proper data collection rate to satisfy the requirements of 4.4.2 of this document.

4.3.1 VERIFICATION OF GRIP ALIGNMENT. Before tests are begun on specimens constituting experimental groups, an initial test shall be conducted on an extra tensile specimen to verify the alignment of the grip system. This specimen shall be equipped with three strain gages in accordance with 6.2.3 of ASTM 3039-76, and the test shall be conducted as specified in that Test Method. If the laboratory has a permanent alignment testing device which can operate up to the loads expected, it may be used instead of this alignment test.

4.4 TESTING PROCEDURE

4.4.1 MAXIMUM GRIP LOAD. Grip loads shall not exceed a value that will result in a local compressive stress greater than 5000 lbf/in^2 through the thickness of the specimen in the grip area. Since the local grip pressure tends to increase somewhat from the outboard edge of the grips (the part nearer to the end of the specimen) to the inboard edge (the part nearer to the longitudinal center of the specimen), the maximum local compressive stress shall be estimated by the following equation:

$$\sigma_c = 1.5\left(\frac{P}{l \cdot b}\right)$$

where σ_c is the estimated maximum local compressive stress
P is the grip load
l is the length of the grip area
b is the width of the grip area

4.4.2 LOADING RATE. The loading rate for tensile testing of both solid and cored specimens shall be 0.12 in/min (3 mm/min). This loading rate should load the specimens for these tests to failure in approximately 2.5 minutes.

4.4.3 DATA COLLECTION RATE. At least 50 data points shall be recorded for each tensile test, with data points taken at equal intervals between the start of the test and failure, with each point comprising simultaneous raw data outputs of tensile load and extension. The data collection rate shall be determined in accordance with the expected time to failure determined from the loading rate and the expected strain at failure. As noted in 4.4.2, the specified loading rate should load the specimens to failure in about 2.5 minutes.

4.4.4 LOAD MEASUREMENT PROCEDURE. Tensile load shall be measured by the output of the load measuring equipment on the testing machine ram.

4.4.5 EXTENSION MEASUREMENT PROCEDURE. Extension shall be measured by the output of a strain-gage extensometer mounted longitudinally on the test specimen (on the flaw side of specimens containing defects) at the longitudinal centerpoint of the specimen and at least 0.5 inch from the edge.

The extensometer and the method of attachment of the extensometer to the test specimen shall meet the requirements of 6.3.1 of ASTM D 3039-76.

4.4.6 DIGITAL RECORDING OF RAW LOAD/EXTENSION DATA FOR TENSILE TESTS. Tensile test data shall be recorded in an ASCII format data file on MS-DOS 720K format 3-1/2" floppy disks. The file name shall uniquely identify the specimen number and the experiment number (if this is not a part of the specimen number itself). The data section of the file shall contain 3 entries for each data group: 1) time from the start of the test, in seconds and tenths; 2) the machine load output in lbf, to 3 significant figures; and 3) the strain as measured by the extensometer in strain units (inches/inch), to 3 significant figures.

4.4.7 MANUAL RECORDING OF SPECIMEN FAILURE INFORMATION. The results of each tensile test shall be recorded on a tensile test specimen data sheet, a sample of which is shown in Appendix A, or in an equivalent digital text file, in addition to the numerical test data recorded in the digital data file. The specimen data sheet or the equivalent digital text file shall include the following information:

1. The specimen number.
2. The experiment number (if not included in the specimen number).
3. The date and time of the test.
4. Conditioning information (temperature, relative humidity and conditioning time.
5. Test room conditions (temperature and relative humidity)
6. The raw dimensional measurements of the specimen, measured in accordance with 3.3 and 3.4 of this document.
7. The core thickness, where appropriate.
8. The tensile loading rate.
9. The tensile load at failure.
10. The tensile strain at failure.
11. In the case of intentionally flawed specimens, the type and size of the flaw.
12. For flawed specimens, an indication of whether the failure occurred at the flaw position or elsewhere.

13. An indication of whether the failure occurred within the gage length (the part of the specimen between the extensometer anchor positions) or elsewhere.
14. Indication of failures within 0.75" of the grip area.
15. An indication of preliminary failures that initiated at loads substantially lower than the ultimate breaking load.
16. A brief description of the mode of failure, and indication of any unusual mode of failure.

Appendix A contains an example of a suggested Tensile Test Specimen Data Sheet.

Section 5

FLEXURAL TESTING

Flexural testing will follow the general procedures outlined in ASTM D 790-90, with the addition of certain procedures from ASTM C 393 for cored specimens, altered as necessary to take into account the large size of the specimens compared to standard flexural test coupons.

The expected breaking load of solid flexural specimens is approximately 2000 lbf, with a center-span deflection at failure of approximately 4.5".

The estimated maximum bending load for cored flexural specimens is in the range of 600-900 lbf, with a center-span deflection at failure of approximately 1.5".

Solid specimens may fail either by tensile failure on the tension side, by compression failure on the compression side, or by a combination of these modes.

Sandwich construction beams (cored constructions) with symmetrical stacking sequences (meaning the laminate stacking sequence in the upper skin is the mirror image of that in the lower skin) typically fail by compressive failure in the compression (top) facing (see 3.3 of ASTM C 393-62).

5.1 TEST APPARATUS AND CONFIGURATION

Figure 3 in Appendix B shows the details of the flexural test setup, which is the same for both solid and cored specimens.

5.1.1 TEST METHOD AND SUPPORT SPAN. The specimens shall be tested using two points of support 20" apart (support span = 20"). Loading shall be accomplished by a two-point loading arrangement with the loading noses 5.0" apart (each 2.5" from the longitudinal centerpoint of the specimen), which is similar to Test Method II of ASTM D 790 and to the two-point load method of ASTM C 393-62.

5.1.2 SUPPORT AND LOADING ASSEMBLY CONFIGURATION. The radius of the contact surface of the supports shall be at least 0.75". The supports shall be rollers which allow the specimen to move freely during the flexural test. It is important that the friction characteristics of the support rollers are well matched in order to prevent the flexural specimens from shifting out of longitudinal alignment with the loading assembly during testing.

The radii of the loading noses shall be 1.5" and the arc of this surface shall extend at least 45° each side of the centerline of the support or nose. As required in ASTM C 393, the loading noses and supports shall be circular in cross-section to within 1% of their diameter and straight to within 0.5% of their length.

The load point on the loading assembly shall be located within 0.0625" of the actual center of the lines of action of the loading noses, and there shall be a notch or other restraining feature to insure that the machine ram engages the loading assembly at the loading point.

The faces of the loading noses and of the supports shall be at least 1/8" (0.125) longer than the maximum specimen width (in other words, at least 4 inches long).

The support assembly shall provide clearance for both the specimen and the loading assembly for deflections up to 5 inches, and shall provide sufficient additional clearance to allow a mirror to be placed under the center of the specimen during testing so that both the tensile and compression faces can be observed.

5.1.3 SURFACE FINISH AND PREPARATION OF SUPPORTS AND LOADING NOSES. The contact surfaces of the loading noses and of roller supports shall be clean and smooth.

5.2 FLEXURAL TESTING MACHINE REQUIREMENTS

5.2.1 ACCURACY AND MEASUREMENT CAPABILITIES. Both the testing machine and its load and deflection measuring devices shall meet the requirements of 5.1 of ASTM D 790 for accuracy and stiffness. The machine shall have outputs for both load and loading nose deflection.

5.2.2 LOAD CAPACITY. The rated load capacity of the crosshead of the flexural test machine shall be at least 2500 lbf.

5.3 TEST PROCEDURE

5.3.1 PLACEMENT OF SPECIMEN IN TEST APPARATUS. The specimen shall be placed in the test jig so that its longitudinal centerpoint is no more than 0.25" from the midpoint of the supports. The midpoint of the loading assembly shall be no more than 0.125" from the midpoint of the supports at the start of loading. The loading assembly shall be constructed so that neither the distance between the loading noses, the alignment of the center of the loading span with center of the support span, nor the position of the load point on the loading assembly can change during the test.

Specimens containing defects shall be placed in the test jig with the defect side down (on the side opposite the loading assembly). Defects are all in the "top" surface of the laminate, that is, the side which was facing up when the sheet from which the specimens were cut was laid up. Unflawed specimens shall also be placed in the test jig with the "top" surface facing down.

The specimen shall be placed on the supports and the loading assembly shall be placed on the specimen in such a manner that the supports and loading noses overhang the specimen edges.

The longitudinal axis of the specimen shall be aligned with the axis of the support span to within 0.5° (corresponding to a 3/16" offset over the 20" support span).

The longitudinal axis of the loading assembly should remain aligned with the support span axis to within 1° (corresponding to a 3/32" offset over the load span). If any specimens shift more than this during the course of a test, that fact should be noted in the comments section of the data sheet for that specimen. When possible, a test which is invalidated by a shift in the loading apparatus should be repeated with a spare specimen from the same batch as the original.

5.3.2 LOADING RATES. Loading rates shall be selected to allow suitable time for observation of the tests without extending the test time so much that rheological processes, rather than simple mechanical phenomena, become important.

For flexural tests of solid specimens, a crosshead loading rate of approximately 0.75 in/min is recommended.

For cored specimens, a crosshead loading rate of approximately 0.375 in/min is recommended. For the flexural specimens used in these tests, this loading rate should result in failure within the 3 to 6 minute time interval recommended by ASTM C 393-62.

Loading rates may be varied slightly from the above recommendations to accommodate the capabilities of individual machines, but in no case shall the loading rate be altered to cause failure in less than 2 minutes or more than 8 minutes.

5.3.3 NORMAL DURATION OF TESTING. The test shall be continued until a definite failure is observed, or until the bending load decreases to 50% of the maximum load observed during the test.

5.3.4 EXTENDED TESTING. Cored specimens may fail by several different modes; compression facing failure, core shear failure, or core/facing bond failure are all possible. Flexural tests should be continued until the applied load drops sharply. A sharp drop in applied load may not occur at the first indication of failure.

In certain phases of the test program, it may be desirable to continue the test past the initial failure in order to determine the order of occurrence of the various failure modes. In such a case, the test plan will specify that the test is to be carried past the failure point as defined in paragraph 5.3.3.

5.3.5 DIGITAL RECORDING OF RAW LOAD/DEFLECTION DATA. Flexural Test data shall be recorded in an ASCII data file on a 5-1/4" or 3-1/2" floppy disk. This file shall have leading entries containing the specimen number, the experiment number (if this is not a part of the specimen number itself), and the date and time of testing. The data section of the file shall contain 3 entries for each data group: 1) time from the start of the test, in seconds and tenths; 2) the crosshead load in lbf, to 3 significant figures; and 3) the deflection as measured by crosshead travel, to 3 significant figures.

Data to be delivered to the Coast Guard shall be on DS/DD DOS format 5.25" floppy disks in ASCII file format. Spreadsheet data may be in SYLK or ASCII file formats.

5.3.6 MANUAL RECORDING OF SPECIMEN FAILURE INFORMATION. The results of each flexural test shall be recorded on the flexural test specimen data sheet, a sample of which is included in **Appendix A**, or in an equivalent digital text file, in addition to the numerical test data recorded in the digital data file. This specimen data sheet or equivalent file shall include the following information:

1. The specimen number.
2. The experiment number (if not included in the specimen number).
3. The date and time of the test.
4. Conditioning information (temperature, relative humidity and conditioning time.
5. Test room conditions (temperature and relative humidity)
6. The raw dimensional measurements of the specimen, measured in accordance with 3.3 and 3.4 of this document.
7. The core thickness, where appropriate.
8. The crosshead loading rate.
9. The maximum bending load recorded.
10. The deflection at the center of the load span at the point at which the maximum bending load is reached.
11. In the case of intentionally flawed specimens, the type and size of the flaw.
12. For flawed specimens, an indication of whether the failure occurred at the flaw position or elsewhere.
13. An indication of whether the primary failure occurred on the tension side or the compression side of the bend.
14. An indication of the position of the primary failure: in the area between the loading noses, directly under one or both loading noses, or elsewhere.
15. An indication of preliminary failures that initiated at loads substantially lower than the maximum bending load.
16. A brief description of the mode of failure, and indication of any unusual mode of failure. This shall include descriptions of failures in which the final failure occurs at deflections substantially greater than that at which the maximum bending load is recorded.

Appendix A contains an example of a suggested Flexural Test Specimen Data Sheet.

Section 6

MISCELLANEOUS

6.1 TESTING FOR GLASS/RESIN RATIO

At least 5 test specimens shall be taken from test coupons originating from each of the solid laminate panels for glass/resin ratio testing. The specimens shall be selected, one per coupon, at random. The tests shall be conducted according to ASTM D-2584, Standard Test Method for Ignition Loss of Cured Reinforced Plastics. A report of the results of these tests shall be delivered to the contracting organization along with the tensile and flexural test data.

6.2 TESTING FOR VOID CONTENT

Void content shall be tested for all panels for which glass/resin ratio testing is done (solid panels only). This testing shall be in accordance with ASTM D-2734, Standard Test Methods for Void Content of Reinforced Plastics. A specimen of solid cured resin, supplied by the manufacturer of the test coupons, and the results of the Glass/resin ratio test (ASTM D-2584) are necessary for completion of this test. A report of the results of these tests shall be delivered to the contracting organization along with the tensile and flexural test data.

6.3 DISPOSITION OF SPECIMENS AFTER TESTING

After testing is complete, the broken specimens are to packaged by experiment group in suitable bags or other containers, labeled with the experiment number, and delivered to the contracting organization along with the test data.

APPENDIX A

SAMPLE DATA SHEETS

[BLANK]

TENSILE TEST SPECIMEN DATA SHEET

SPECIMEN NUMBER	EXPERIMENT NUMBER	TEST DATE

CONDITIONING

TIME ________ TEMP ________ HUMIDITY ________

TEST ROOM

TEMP ________ HUMIDITY ________

MEASUREMENTS

THICKNESS

1 ________
2 ________
3 ________
4 ________
5 ________
6 ________
AVG. ________

WIDTH

1 ________
2 ________
3 ________
AVG. ________

CORE THICKNESS

____

LAMINATE CROSS SECTION

____

LOAD RATE (in/min)	FAILURE LOAD (lbf)	STRAIN AT FAILURE (in/in)
________	________	________

DEFECT SIZE AND TYPE	FAILURE AT DEFECT?	FAILURE IN GAGE AREA?	GRIP FAILURE?
________ ________	YES ☐ NO ☐	YES ☐ NO ☐	YES ☐ NO ☐

PRELIMINARY FAILURES

LOAD	FAILURE TYPE
________	________
________	________

DESCRIPTION OF FAILURE

____

____

____

____

FLEXURAL TEST SPECIMEN DATA SHEET

SPECIMEN NUMBER	EXPERIMENT NUMBER	TEST DATE

CONDITIONING

TIME ________ TEMP ________ HUMIDITY ________

TEST ROOM

TEMP ________ HUMIDITY ________

MEASUREMENTS

THICKNESS

1 ________
2 ________
3 ________
4 ________
5 ________
6 ________
AVG. ________

WIDTH

1 ________
2 ________
3 ________
AVG. ________

CORE THICKNESS ________

LAMINATE CROSS SECTION ________

LOAD RATE (in/min)	FAILURE LOAD (lbf)	DEFLECTION AT FAILURE (in)
________	________	________

DEFECT SIZE AND TYPE

____

____

FAILURE

AT DEFECT?

YES ☐

NO ☐

COMPRESSION SIDE ☐

TENSION SIDE ☐

BETWEEN LOAD NOSES ☐

UNDER LOAD NOSE ☐

ELSEWHERE ________

PRELIMINARY FAILURES

LOAD	FAILURE TYPE
________	________
________	________

DESCRIPTION OF FAILURE

____

____

____

____

APPENDIX B

FIGURES

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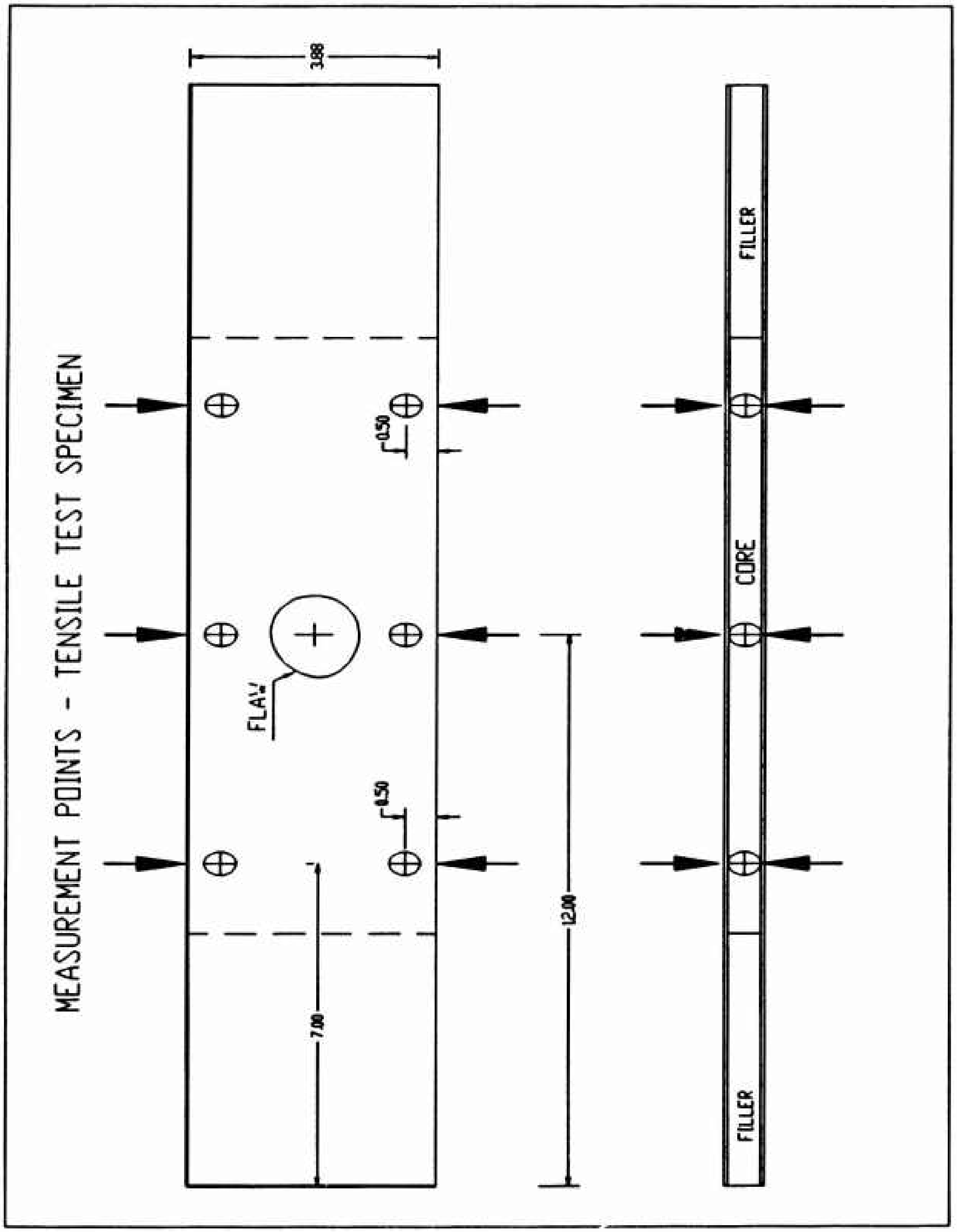

Figure 1. Tensile Specimen Measurement Points

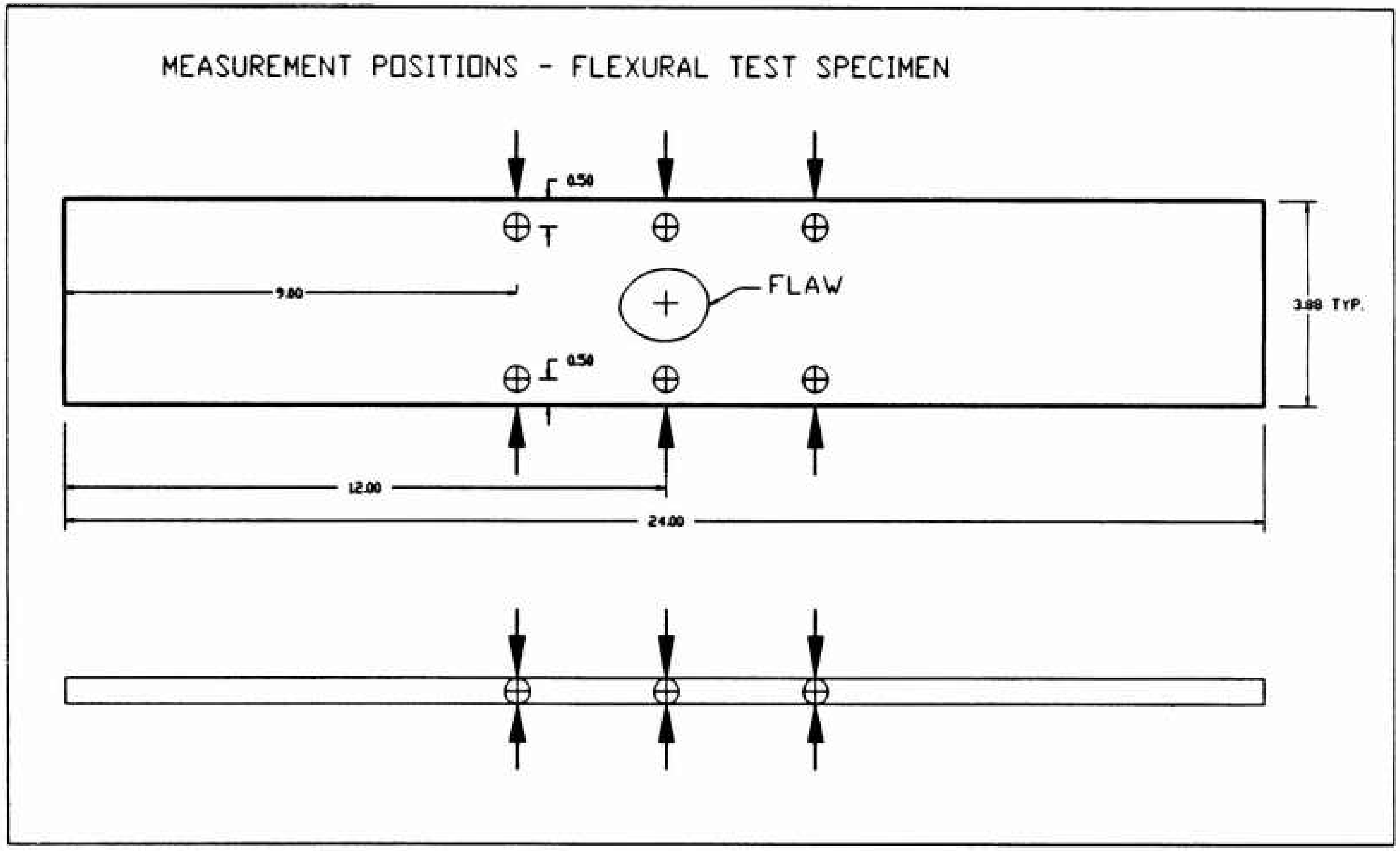

Figure 2. Flexural Specimen Measurement Points

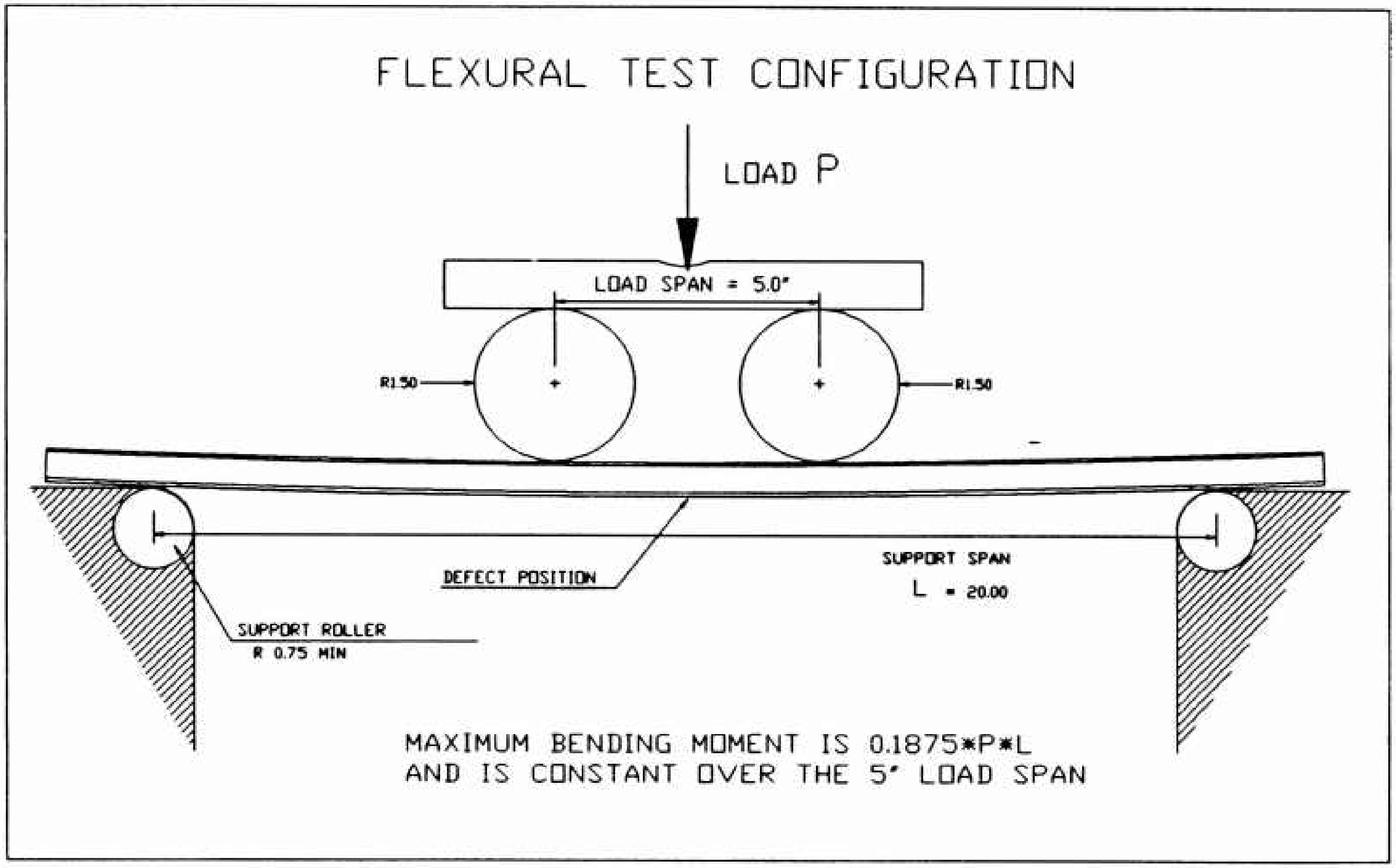

Figure 3. Flexural Test Setup

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ENCLOSURE 3

Test Plan

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Section 1

BACKGROUND

Under Delivery Order DTCG39-91-F-E33B16 to Contract DTCG39-91-D-E33A21, the U.S. Coast Guard tasked MAR, Incorporated with developing a Test Plan for *Structural Evaluation of Glass-Reinforced Plastic Defects*. This Test Plan supplements a Test Coupon Production Specification (TCPS) and a Test Procedure also developed under this delivery order. The TCPS provides the specifications for making the test coupons; the Test Procedure details the requirements for conditioning the coupons and for testing individual coupons; and this Test Plan describes the independent variables to be tested and provides a statistical basis for determining combinations of flaws and core types that have little impact on strength. Those combinations that have little impact on strength can be deleted from the final phase in which the remaining combinations are tested over a range of flaw sizes.

1.1 APPLICABLE DOCUMENTS

DOT Order 1700.18B. 1976. *Acquisition, Publication, and Dissemination of DOT Scientific and Technical Reports.*

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM) STANDARDS

ASTM Standards are contained in *Annual Book of ASTM Standards*, by the American Society for Testing and Materials.

ASTM C 274-68 (Reapproved 1988). *Standard Definitions of Terms Relating to Structural Sandwich Constructions*, Vol. 15.03, 1990.

ASTM C 393-62 (Reapproved 1988). *Standard Test Methods for Flexural Properties of Flat Sandwich Constructions*, Vol. 15.03, 1990.

ASTM D 790-90. *Standard Test Method for Flexural Properties of Fiber-Resin Composites*, Vol. 08.01, 1991.

ASTM D 3039-76 (Reapproved 1989). *Standard Test Method for Tensile Properties of Fiber-Resin Composites*, Vol. 15.03, 1990.

ASTM E 6-83. *Standard Definitions of Terms Relating to Methods of Mechanical Testing*, Vol. 03.01, 1990.

ASTM E 1325-90. *Standard Terminology Relating to Design of Experiments*, Vol. 09.01, 1990.

Section 2

INTRODUCTION

In recent years, composite materials, especially Glass-Reinforced Plastics (GRP), have been used extensively in marine vessels for hulls, decks, and other structural applications. Unfortunately, there is little information about the significance of defects such as voids or delaminations. A question often asked by marine inspectors is "how large does a defect have to be before it is unsafe." At present, the Coast Guard has no method, other than subjective visual inspections and ASTM flexural, tensile, and compressive tests of sample coupons, to verify material properties, soundness of joints, the integrity of internal laminations, and other aspects of composite material physical integrity.

Coast Guard Navigation and Inspection Circular No. 8-87, *Notes on Design, Construction, Inspection, and Repair of Fiber-Reinforced Plastic (FRP) Vessels*, is used to inspect and certify GRP ships and boats. Visual inspection is the key to the present inspection process. However, since more larger sized vessels are being constructed of GRP, there is a need to reassess the inspection process used by Coast Guard personnel to certify vessels. Coast Guard Report No. CG-D-02-91, *Nondestructive Evaluation of Fiberglass Marine Structures*, showed that under laboratory conditions, even the best ultrasonic devices could only detect defects in the laminate 68% of the time. Clearly, if defects are hard to detect in a laboratory setting using state-of-the-art ultrasonic devices, then it can be assumed that many defects are not being discovered using the present method of visual inspection.

Solid GRP and various sandwich composites have been used for the construction of pleasure boats for many years in the United States. Overseas, this same construction is now being used on larger vessels including ferries and other passenger carriers. Since these large vessels come under Coast Guard regulations and inspections in the United States, safe and thorough inspections will require the development of standard rejection and acceptance criteria.

With this in mind, the following sensitivity study will help define at what point a flaw is acceptable or not. In turn, this information will be used when reviewing nondestructive inspection methods and devices that are currently being developed in the marine industry.

Section 3

APPROACH TO THE TEST PLAN

One approach that could be used for testing composite samples is to test every combination of flaw type, core type, and flaw size of interest. As discussed in the following paragraphs, there are four core types including solid. There are nine flaw types for cored coupons. There are only eight for solid coupons since core filling does not apply. As discussed in paragraph 4.6, a minimum of 24 coupons should be tested for each flaw type and core type combination. Also, tensile coupons and flexural coupons for all combinations need to be tested. Thus, in order to test every combination, 1680 test coupons would be required (35 core/flaw types x 24 coupons each x 2 test types). Samples of this size would provide a reasonably accurate estimate of the mean breaking strength for unflawed coupons and for three different flaw sizes. However, the population variances would not be well defined with such a limited number of coupons.

We would also like to compare flawed and unflawed samples of each core and flaw type to determine if the largest practical flaw actually decreases the strength of the coupons. The following steps describe a method for comparing core types and flaw types to determine if the flaws have a measurable effect on coupon strength. If the flaw does not have a measurable effect, that core and flaw type can be eliminated from further consideration. Those combinations of core and flaw type that show reductions in strength from unflawed coupons will be tested at other flaw sizes as described in paragraph 4.5. A better estimate of variance will also be obtained from the tests described in paragraphs 4.1 and 4.2.

3.1 FLAW TYPES

The following flaws (defects) are to be included in the initial phase of testing:

- Unflawed
- Flawed
  - Voids
  - Uncured Resin
  - Dry Fibers
  - Delamination
  - Cracked Skin
  - Impact Damage
  - Core Filling (for cored coupons only)
  - Lapped Reinforcement
  - Shop Floor Dirt.

Conclusions based upon the results of the initial phases might eliminate some of the flaw types from consideration in later phases.

3.2 CORE TYPES

The following core types will be used. Lay-up details are included in the TCPS, which is provided separately.

- Solid
- Airex™ cored
- Divinycell™ cored
- Balsa cored.

3.3 INDEPENDENT VARIABLES

3.3.1 LIST OF POTENTIAL INDEPENDENT VARIABLES. Independent variables are those factors that might affect the mechanical properties of the laminate and are either varied intentionally from one coupon to another or might vary unavoidably.

3.3.1.1 **Flaw Characteristics.** The following is a list of flaw characteristics:

- Flaw type
- Flaw size
- Flaw size/coupon width ratio
- Number of laminate layers affected the by flaw.

3.3.1.2 **Location Variables.** The following is a list of the location variables:

- Panel from which coupon is cut
- Location of coupon on panel.

3.3.1.3 **Dimensional Variables.** The following is a list of the dimensional variables:

- Coupon width
- Coupon thickness
- Length to width ratio of coupon.

3.3.1.4 **Lay-up Physical Variables.** The following is a list of the physical variables:

- Lay-up schedule and stacking sequence
- Fiber orientation
- Person doing the layup
- Glass-to-resin ratio
- Air bubbles or voids in resin
- Foreign inclusions
- Wrinkles in cloth
- Other flaws in glass or resin.

3.3.1.5 Coupon Physical Variables. The following is a list of the coupon physical variables:

- Smoothness of edges
- Roughness of surface
- Condition around edges of the flaw.

3.3.1.6 Material Variables. The following is a list of the material variables:

- Type of polyester resin
- Amount and type of accelerator used
- Amount and type of catalyst used
- Batch of resin
- Batch of reinforcement materials.

3.3.1.7 Environmental Variables. The following is a list of the environmental variables:

- Lay-up temperature
- Humidity at layup
- Pressure during cure
- Temperature during cure
- Cure time.

3.3.1.8 Post-Production Variables. The following is a list of the post-production variables:

- Preconditioning time
- Preconditioning temperature
- Preconditioning humidity/wetting
- Preconditioning loads
- Exposure to ultraviolet radiation
- Loading rate during test.

3.3.2 DISCUSSION OF INDEPENDENT VARIABLES. Of the independent variables listed in paragraph 3.3.1, most can be eliminated from consideration due to careful experiment design and due to controls placed on the materials, on the layup and curing of the panels, on the preparation of the test coupons, on the storage of the coupons before testing, and on the testing itself. The following sections describe measures required by the TCPS, the Test Procedure, and by this Test Plan, which allow elimination of many of the potential independent variables from consideration.

3.3.2.1 Flaw Characteristics. **Flaw type** is obviously retained as an independent variable. However, during the initial phase of testing, if a given flaw type fails to produce significant changes in coupon strength when the largest flaw size of a given flaw type is tested, then that flaw type will be considered for elimination as an independent variable in further testing .

Flaw size is retained as an independent variable. Since coupon width is constant, **flaw size/coupon width ratio** is determined only by the flaw size.

The **number of laminate layers affected by the flaw** is controlled by the flaw production technique and does not vary for a given flaw; therefore, it can be eliminated as a variable.

3.3.2.2 <u>Location</u>. **Variations** of properties **between panels** are eliminated from consideration as a variable because all coupons for a given experiment come from the same panel, as described in Section [illegible] of this Test Plan. In certain cases, pooled sample variances (but not means) can be com[illegible]ng data from more than one panel after suitable tests have been conducted to ver[illegible] appropriate.

[illegible] possibility that mechanical properties might vary from one **location** to another **on a given panel** cannot be discounted. Therefore, such a variation can be considered a valid variable. Randomization of the positions on the panel of coupons having various flaw sizes will be used to minimize the effects of this variable.

3.3.2.3 <u>Dimensional</u>. **Coupon width and length** are standardized by the TCPS, thus eliminating significant variations. In addition, the width and thickness of each coupon is measured before testing. Important specimen properties are calculated on actual width and nominal thickness, and import[illegible]al properties are calculated on actual cross-sectional area.

Although lay-up procedures are closely controlled, the **coupon thickness** might vary somewhat since the lay-up schedule, rather than actual thickness, is specified. Although most mechanical properties are primarily dependent upon the cross-sectional area of reinforcement, which is tightly controlled, unavoidable variations in thickness might affect mechanical properties. As stated previously, actual thickness is measured and actual cross-sectional area is used where appropriate when calculating mechanical properties.

3.3.2.4 <u>Lay-up Physical Variables</u>. **Lay-up schedule and stacking sequence** and **fiber orientation** are tightly specified by the TCPS and are eliminated as independent variables.

Properties of hand lay-up laminates normally vary from one lay-up technician to another. Among the factors involved in these variations are **glass/resin ratio, void content, foreign inclusions, wrinkles**, and **other unintentional flaws**. The primary control over such variations could be ensured by specifying that one technician have direct control over all lay-up operations. Quality Control (QC) inspections by supervisory personnel ensure that significant flaws, such as wrinkles or foreign inclusions, will not be included in test coupons. During the testing procedure, glass/resin ratio and void content will be tested for coupons from each panel. These variables are considered to be eliminated as independent variables, but no doubt make up a significant part of the experimental error.

3.3.2.5 <u>Coupon Physical Variables</u>. The **smoothness of the cut edges of coupons** is controlled by the TCPS to a sufficiently close tolerance so that any stress concentrations arising from machining defects are small when compared with those due to intersections of voids and air bubbles in the layup with the cut edge.

The **roughness of the top and bottom surfaces of the coupons** is controlled by the lay-up procedure: the bottom by the smooth, waxed lay-up table and the top by use of a fine-weave material and by the consistency in the technique of the lay-up technician. Small variations in top surface roughness are unavoidable, and variations in strength due to this factor are part of the experimental error.

Conditions around the flaw edges might influence the effects of the flaw on the mechanical properties of the coupon. These are controlled as tightly as possible by the detailed specifications for flaw production and by the consistency of the lay-up technician.

3.3.2.6 **Material Variables.** Material variables are all controlled tightly by the TCPS and can be eliminated as independent variables. The accelerator is pre-mixed in the resin by the manufacturer. The same type of resin from the same batch is used for the entire project. Reinforcement materials are similarly controlled. The catalyst ratio is specified to a much tighter range than that over which any variation in cured resin properties might result.

3.3.2.7 **Environmental Variables.** All of the environmental variables are controlled closely by the TCPS and can be eliminated from consideration as independent variables.

3.3.2.8 **Post-Production Variables.** All of the post-production variables are controlled by the TCPS or by the Test Procedure or by both. Since all coupons for a given experiment come from the same panel, they will have an identical cure history. Precautions are specified to ensure that coupons are not subject to any mechanical loads or ultraviolet radiation between production and testing.

Environmental conditions between production and testing are controlled by specified temperature and humidity ranges and by packaging specifications for test coupons. In addition, the experiments in this Test Plan are designed in such a manner that direct comparisons between the mean properties of coupons are only made for coupons originating from the same laminate panel.

The loading rate during testing is a specified constant for all experiments of a given type, i.e., tensile, cored flexural and solid flexural, and is thus eliminated from consideration as a variable.

3.4 DEPENDENT VARIABLES

The following is a list of the dependent variables:

- Ultimate breaking strength (tensile and flexural)
- Elastic modulus (tensile)
- Flexural modulus (flexural)
- Coupon elongation at failure (tensile)
- Coupon deflection at failure (flexural).

Of the dependent variables, the breaking strength is the one that is considered the most important and will be given the most attention during the experimental analysis. However, the analysis procedures described herein would not differ significantly if other dependent variables were to be evaluated.

The term "breaking strength" is used throughout this document to indicate the primary dependent variable means, specifically the breaking stress for tensile coupons and the maximum fiber stress at failure for flexural coupons. These stresses are defined in detail in paragraph 5.1 of this Test Plan.

3.5 DESIGN BREAKING STRENGTH

The ultimate goals of this Test Plan are to determine if defects in test coupons lower the expected mean value of the breaking strength and, further, if these defects introduce more variability in the measured breaking strengths of the defective test coupons than that which is observed for unflawed test coupons. Either a decrease in mean strength or an increase in the variability of the strengths of individual defective coupons, or both, would lead to the conclusion that the presence of defects increases the likelihood that the strength of an individual coupon would fall below some acceptable level of strength.

3.6 STEPS IN THE EXPERIMENT

The steps recommended for this experiment are described briefly below. Section 4 expands on this discussion.

Steps 1 through 4 constitute a screening experiment designed to eliminate as many flaw and core types as possible from detailed consideration. Steps 1 and 2 compare the variances of samples while steps 3 and 4 compare the mean breaking strength. Step 5 provides more detail for the remaining significant combinations of flaw and core type.

STEP 1

This step determines the sample variances of coupon breaking strengths for unflawed coupons and for coupons having a large size flaw of each flaw type, for both a solid layup and for <u>one</u> of the cored type layups. There are 19 combinations in all, 10 for the cored coupons and 9 for the solid coupons Twelve test runs each are recommended to resolve differences between variances as discussed in paragraph 4.1. For the solid coupons, it is convenient to test samples of 12 flawed and 12 unflawed coupons of each flaw type. The solid coupon tests can then be used in step 3 to estimate differences in mean values.

This results in testing 192 solid tension and 192 solid flexural coupons ((8 unflawed + 8 flaw types) x 12 coupons each) as shown in **Table 3-1**. Each panel of solid coupons will contain 24 coupons (12 unflawed + 12 flawed of the same flaw type). Sixteen panels are required (8 flaw types x 2 test types). An additional 240 cored coupons ((1 unflawed + 9 flaw types) x 12 coupons each x 2 test types) are needed for tensile and flexural tests. When testing for variance, it is not critical that the unflawed and flawed coupons come from the same panel. The 12 coupons of each flaw type must come from one panel, however.

Two flaw types can be laid up together (24 coupons per panel), so 10 panels will be required. A total of 624 coupons (26 panels) will be tested in this step. Sample variances for each group of 12 coupons will be computed from the test results. Step 2 compares the sample variances obtained.

Table 3-1. Number of Test Coupons for Step 1

Flaw Type	Solid Coupons*	Cored Coupons
Unflawed	192	24
Voids	24	24
Uncured Resin	24	24
Dry Fibers	24	24
Delamination	24	24
Cracked Skin	24	24
Impact Damage	24	24
Core Filling	—	24
Lapped Reinforcement	24	24
Shop Floor Dirt	24	24
Total	384	240

* Note: Data from solid test coupons is used in Step 1 and in Step 3

STEP 2

Using the test data from step 1, this step determines if the population variance of strength for flawed coupons is statistically different from the unflawed population variance using the F-Test. Depending on the results of this test, we will either conclude that the population variances for flawed and unflawed coupons are equal or that their population variances are different. If we conclude that the variances are different, the measured sample variances for unflawed and flawed coupons will be used as the population variances. If we conclude that the population variances are equal, the variance of the unflawed samples will be used for both.

STEP 3

This step determines an estimate of the population mean strengths for unflawed and flawed (large size flaw) coupons for each flaw and core type. The test results for solid coupons from step 1 are used, so only cored samples are tested in this step. The cored coupon breaking strengths can be pooled, assuming a common variance. This significantly reduces the number of tests with little loss of accuracy, even if the individual variances are not, in fact, equal. As discussed in paragraph 4.3, 4 flawed and 4 unflawed coupons must be tested for each of the 27 flaw and core type combinations (only cored coupons are included here). A set of coupons must be produced for tensile tests and another for flexural tests. This gives a total of 432 coupons (8 x 27 x 2). Three different flaw types can be included on one 24-coupon panel. Thus, a total of 18 panels must be manufactured for this test. The set of four flawed and four unflawed coupons for each flaw type/core type combination must come from the same panel. The number of coupons needed is tabulated in **Table 3-2**.

Cored coupon sample means and variances are computed from the test results of this step. Sample means and variances for solid coupons are also computed using the solid coupon test results from step 1.

Table 3-2. Number of Test Coupons for Step 3

Flaw Type	Core Type		
	Airex™	Divinycell™	Balsa
Unflawed	72	72	72
Flawed			
Voids	8	8	8
Uncured Resin	8	8	8
Dry Fibers	8	8	8
Delamination	8	8	8
Cracked Skin	8	8	8
Impact Damage	8	8	8
Core Filling	8	8	8
Lapped Reinforcement	8	8	8
Shop Floor Dirt	8	8	8
Total	144	144	144

STEP 4

The following hypotheses are tested in this step:

(1) For each flaw type, the population mean breaking strength for coupons with large flaws equals the mean for the unflawed coupons.

(2) For different core types, the population mean breaking strength for one core type equals that for another core type.

The sample means and variances computed in step 3 are used. A pooled t-test is used to compare the mean breaking strengths. That is, the test results for all three cored samples are pooled when comparing flawed versus unflawed results. No pooling is necessary when comparing solid coupon results. For cored samples, the test results for both flawed and unflawed coupons are also pooled when comparing the effect of the core type.

If hypothesis (1) is true for a given flaw type with a large size flaw, then there is little point in testing smaller flaw sizes because the results will be equal to unflawed results (at least in a statistical sense). For a given flaw type, there are four comparisons: solid tension samples; cored tension samples (combining the 3 non-solid core types); solid flexural samples; and cored flexural samples.

Hypothesis (1) might be true for any or all of these comparisons. If hypothesis (1) is true, then that combination of flaw type and core type should be eliminated from testing in step 5. If true for non-solid core types, all three non-solid core types should be eliminated for that flaw type. However, if the population variances computed in step 2 for the flawed samples are greater than that of unflawed samples, despite apparent equality of means, then the flaw type should be evaluated further in step 5.

Hypothesis (2) might be true for any two or all three of the non-solid core types. Solid samples are assumed to differ significantly from the non-solid core samples and are not compared with them. Data and recommendations for eliminating a core type shall be presented. All core types will be used for further testing as detailed in Step 5 unless the contracting organization calls for eliminating one or more core types based upon the results of the tests of hypothesis (2). If hypothesis (2) is true for a pair of core types for the flaw type being considered, then either one can be eliminated from further testing. The results of testing the other in step 5 can be used for both.

STEP 5

In this step, additional testing is conducted for smaller flaw sizes for each core/flaw type that has not been eliminated in the four previous steps. In addition to unflawed coupons, at least three flaw sizes should be investigated. The data obtained previously for the large flaw size and the unflawed coupons can be used; however, it would be better to repeat the test for all flaw sizes using coupons cut from the same panel of material. At least six coupons should be tested at each flaw size. Thus, each flaw type/core type combination requires a separate panel of 24 test coupons. The total number of test panels depends on the number of combinations remaining after the tests in the previous steps have been conducted.

The data collected in this step are used to plot curves of breaking strength versus flaw size. Curves of both the mean breaking strength and the minimum breaking strength will be plotted. The minimum breaking strength curve is plotted at three standard deviations below the mean curve.

Section 4

TEST PLAN

Before beginning a statistical analysis of test samples, some assumptions must be made about the real-world population of test coupons. Each combination of core type, flaw type, and flaw size has associated with it a set of properties such as breaking strength, modulus of elasticity, etc. Throughout this section, we will use breaking strength as the dependent variable of interest. A parallel analysis can be used for other measured variables if required.

If we tested every coupon that could be made (the entire population) having a particular combination of flaw and core types, we would find that the breaking strengths have a mean value, μ, and a standard deviation, σ. The "population" exists only in theory and is very large. In fact, it is infinite in size.

In this Test Plan, we assume that the breaking strengths of both flawed and unflawed samples are normally distributed. That is, the strengths measured for all coupons having a given flaw type, flaw size, and core type will vary randomly in a normally distributed manner about the mean value. This appears to be true from previous tests of unflawed coupons. There is no reason to believe that flawed coupons will behave differently. As with nearly all materials, the properties of the materials making up the composite will vary in strength about the mean in a normally distributed manner. The random testing errors are also expected to be normally distributed. Finally, the variations in flaw characteristics should be normally distributed and should cause normally distributed strength variations. Therefore, the statistical methods used in this test plan are based on normally distributed random variables. Little work has been done on the statistics of other than normally distributed random variables.

It might seem that only the mean values of breaking strength are important; however, on further investigation, it becomes apparent that the standard deviations are equally important. The minimum likely breaking strength determines the design load. This minimum breaking strength can only be determined if we have good estimates of both the mean breaking strength and the standard deviation for the population of test coupons because the minimum strength is some multiple of the standard deviation below the mean.

If the population mean μ and the population standard deviation σ were known with certainty, it would be easy to predict the probability that the breaking strength of a given coupon would exceed some minimum value. However, since only a few coupons from the theoretically infinite population can be tested in any real experiment, it is necessary that the population mean and variance be estimated using relatively small *samples* or groups of coupons. These estimating parameters are the sample mean $\bar{x}$ and the sample standard deviation s, where:

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \qquad s = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n - 1}}$$

x_i = breaking strength of individual coupons
n = number of coupons in the sample.

It would be convenient to assume that the standard deviation is the same for flawed coupons and unflawed coupons, but there is no reason to believe that this is true. The population variance is caused by three primary factors: the variations in material properties everywhere except where the flaw is located; the random error in the measuring process; and variations of properties in the vicinity of the flaw. The first two are common to both flawed and unflawed coupons. The third, variation of properties in the vicinity of the flaw, should be higher for flawed samples than for unflawed samples. Thus, it will be assumed that the breaking strength for flawed coupons will have a population variance (σ_2^2) at least as great as the population variance (σ_1^2) for unflawed coupons. Because of this, a single-sided statistical test for equality of variances is most appropriate. It should be noted that even if this assumption is true, it is still possible that the *sample* variance (s_1^2) for a small sample of unflawed coupons could be greater than that for a small sample of flawed coupons (s_2^2).

It is reasonable to assume that the breaking strength population means for flawed coupons (μ_2) will be equal to or lower than those for unflawed coupons (μ_1). Therefore, single-sided statistical tests will be also be used in the statistical analysis for differences in mean breaking strengths between flawed and unflawed samples. When comparing two core types, either could have a lower breaking strength; therefore, two-sided test for comparing mean values must be used in this case.

4.1 STEP 1

The first step determines the sample variance of flawed and unflawed coupons for one of the three non-solid core types (i.e., Airex™) and for solid coupons. For non-solid cored coupons, we are making the assumption that the breaking strength has the same variance regardless of core type. This seems reasonable since the cores are the same thickness and the skin materials and thicknesses are the same. The primary strength of the coupon is determined by the skin. Since the skins are the same for all core types, we would expect the strength variances to be equal. This reduces the number of cored coupons tested by a factor of three.

For the variance evaluation, we will take a bold approach and test a flawed coupon having the largest flaw size possible. If the flaw tested is too small, then we might conclude incorrectly that the variance in strength for a flawed coupon is not significantly different from that of an unflawed coupon. On the other hand, if the flaw size that is chosen is too large, then the variance might be exaggerated because of the proximity of the flaw to the edges of the coupon.

For cored samples, there are nine different flaw types plus the unflawed type coupons. We need to test a sufficient number of tensile and flexural coupons of each of the 10 types in order to determine whether flawed samples have different variances than those of the unflawed samples. The samples for each of the nine flaw types will be compared to the single sample of the unflawed coupons.

The same tests could be conducted for solid coupons except that there are only eight flaw types. It is beneficial, however, to repeat the tests on unflawed coupons for each type of flaw since this permits the same data to be used in evaluating the sample means in step 3. When assessing the differences in the means, both flawed and unflawed samples must be cut from the same panel. That is, the unflawed samples and flawed samples for each flaw type being compared must be laid up together. This results in more tests than are necessary to assess the variance but lessens the number of tests overall.

Sample variance is easily calculated once test data are available. The question that must be answered up front is this: *How many test runs are needed to obtain sample variances that are sufficiently accurate estimates of the population variances of flawed and unflawed coupons to permit a reliable comparison of the two?* The sample variance, s, that is computed as a result of testing is only an approximation of the true population variance, σ. To make matters worse, we are comparing approximations, i.e., the sample variance of the flawed samples to that of the unflawed samples. This problem occurs often in statistical analysis, and there is a well-defined approach for addressing it. The F-Distribution is used to determine the critical ratio between the two sample variances. This critical ratio divides the range of sample variance ratios into two regions. If the measured sample variance ratio is below the critical ratio, then we conclude that the population variances are equal. Above the critical ratio, we conclude that the two samples come from populations having different variances. The level of confidence and the number of test runs in each sample are factors in determining the critical ratio in the F-Distribution.

For the F-Distribution, the statistic being measured is:

$$f = \frac{\sigma_1^2 s_2^2}{\sigma_2^2 s_1^2}$$

s_1, σ_1 are the sample and population standard deviations, respectively, of unflawed coupons.

s_2, σ_2 are the sample and population standard deviations of flawed coupons.

This statistic has $\nu_1 = n_1-1$ and $\nu_2 = n_2-1$ degrees of freedom where n_1 and n_2 are the sample sizes.

Values of this statistic are available in statistical tables for various confidence limits and sample sizes. To simplify the analysis, we will use the same number of coupons for both the flawed and unflawed samples. The values of f_C for 0.95 and 0.90 confidence levels and for different sample sizes are shown in **Table 4-1**. The critical ratio of sample standard deviations is also given in **Table 4-1**, using the assumptions that the population standard deviations are equal. As can be seen by inspecting the equation for f, the values in the "critical ratio" column are simply the square roots of the values of the f statistic. **Table 4-1** should only be used to test the hypothesis that the population variances are equal. The table values are based on a single-sided test, assuming that σ_2 will always be at least as large as σ_1.

If the ratio of the measured sample standard deviations s_2/s_1 is greater than the critical ratio listed in **Table 4-1** for a given sample size, one can conclude, with 95% or 90% confidence, that the flawed population standard deviation σ_2 exceeds the unflawed population standard deviation σ_1. In accordance with the assumptions made in the design of this test, any measured ratio of standard deviations less than the critical ratio leads to the conclusion that the population standard deviations are equal.

Table 4-1. Critical Standard Deviation Ratios for F-Distribution

Number of Coupons in Each Sample	95% Confidence		90% Confidence	
	f_c	Critical s_2/s_1 ratio	f_c	Critical s_2/s_1 ratio
2	167	12.91	40	6.32
3	18.87	4.34	9.01	3.00
4	9.26	3.04	5.38	2.32
5	6.37	2.52	4.12	2.03
6	5.05	2.25	3.45	1.86
7	4.29	2.07	3.06	1.75
8	3.79	1.95	2.79	1.67
9	3.44	1.85	2.59	1.61
10	3.17	1.78	2.44	1.56
11	2.98	1.73	2.32	1.52
12	**2.82**	**1.68**	**2.23**	**1.49**
13	2.68	1.64	2.15	1.46
14	2.58	1.61	2.08	1.44
15	2.48	1.57	2.02	1.42
16	2.40	1.55	1.97	1.40
17	2.33	1.53	1.93	1.39
18	2.27	1.51	1.89	1.37
19	2.22	1.49	1.86	1.36

The choice of the number of runs is rather arbitrary. Note that larger samples allow conclusions based upon smaller ratios of sample variances. As the number of coupons in an individual sample increases, the critical standard deviation ratio decreases. In other words, you can differentiate variances that are closer together. However, the resolution gained per additional experimental run diminishes as the number of runs increases. Based on this table, 12 runs appears to be a good number of runs for the variance tests. Note that in a sample size of 12 means, one sample of 12 unflawed coupons and another sample of 12 flawed coupons are compared.

A sample size of 12 results in testing 192 solid tension and 192 solid flexural coupons ((8 flaw types + 8 unflawed) x 12 coupons each). Each panel of solid coupons will contain 24 coupons (12 flawed + 12 unflawed of the same flaw type). Sixteen panels are required (8 flaw types x 2 test types). An additional 240 cored coupons ((9 flaw types + 1 unflawed) x 12 coupons each x 2 test types) are needed for tensile and flexural tests. When testing for variance, it is not critical that the unflawed and flawed coupons come from the same panel. The 12 coupons of each flaw type must come from one panel, however. Two flaw types can be laid up together (24 coupons per panel), so 10 panels will be required. A total of 624 coupons (26 panels) will be tested in this step. When testing is completed, the sample variances for flawed and unflawed samples will be computed. Step 2 compares the sample variances obtained.

4.2 STEP 2

At the start of this step, it is assumed that 12 coupons of each flaw type, for both cored and solid coupons and tension and flexural tests, have been tested per step 1 and that sample variances have been computed. In step 2, the sample variances will be compared to determine if the population variances are different for flawed and unflawed coupons. For the cored coupons, samples of each flaw type will be compared to the single sample of unflawed coupons. For the solid coupons, each flaw type will be compared to the sample of unflawed coupons cut from the same panel of material. Further information can be obtained by comparing all unflawed solid samples to one another. This would indicate how samples vary when laid up at different times and under different conditions.

The following discussion applies to each of the pairs of samples, one flawed and one unflawed. The null hypothesis, H_0, is that the population variances for flawed and unflawed coupons are equal. The alternative hypothesis, H_1, is that the flawed coupons have a greater variance than do unflawed coupons.

H_0: $\sigma_1^2 = \sigma_2^2$

H_1: $\sigma_1^2 < \sigma_2^2$

As indicated in **Figure 4-1**, the critical region is the high end of the F-Distribution such that the area, α, under the distribution curve is

α = 1 - Confidence Level

For a Confidence Level of 0.95 (95%), $\alpha = 0.05$

The critical value of f, f_C, is at the left end of the critical region.

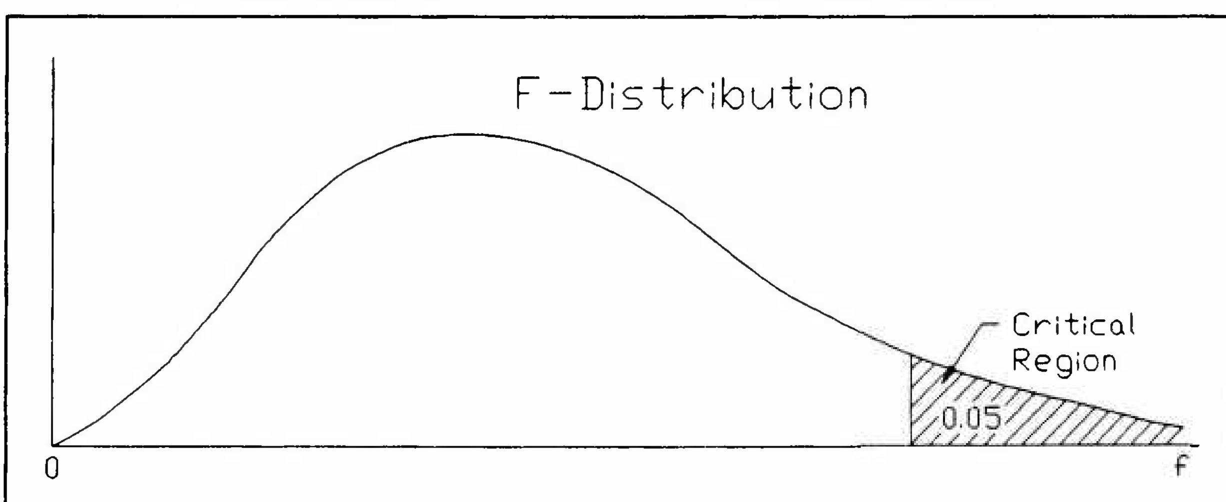

Figure 4-1. Critical Region for F-Distribution

If the two samples come from the same population, then their f-statistic will fall below the critical region 95% of the time. If the computed ratio of the sample variances is below the critical region, the null hypothesis is assumed to be true.

If the computed ratio of the sample variances is within the critical region, the null hypothesis could still be true since this will occur 5% of the time. However, if the ratio is within the critical region, we will conclude that the alternative hypothesis is true.

In all cases, the population variance of unflawed coupons will be set equal to the sample variance of unflawed coupons. If we conclude that the null hypothesis is true, we will use the sample variance of the unflawed coupons as the population variance for both flawed and unflawed coupons. If we conclude the alternative hypothesis is true for a pair of samples, the population variance for flawed coupons will be set equal to the computed sample variance for this flaw type. For cored coupons, the same variance will be used for all core types.

One further question will be investigated: *For a given certainty, what is the highest ratio of population variances which could have produced the measured sample variance ratio?* For example, if we want to choose the highest population variance ratio with 95% certainty and a sample size of 12, we would use the value of f_C of 2.82 (See **Table 4-1**).

Since

$$f_C = \frac{\sigma_1^2 s_2^2}{\sigma_2^2 s_1^2}$$

we can substitute for σ_2

$$\sigma_2 = k \cdot \sigma_1$$

Then, using the measured s_2/s_1 and the chosen f value, we can calculate k. Thus, with 95% certainty, we will not have a higher population variance for flawed coupons than k^2 times the population variance of the unflawed coupons. This is statistically the worst case, i.e., the worst case given the chosen level of certainty. There is still a 5% chance that the population variance ratio is even greater.

4.3 STEP 3

The next step is determining the mean values for the flawed and unflawed samples. The key question is again: *How may coupons must be tested to obtain an adequate sample?* If the population variances were known, this would be an easy question to answer. However, since only sample variances are known, the problem is more complex. **Figures 4-2** and **4-3** illustrate the key features of the problem. **Figure 4-2** illustrates the single-sided case used when comparing flawed and unflawed coupons. **Figure 4-3** shows the case where two core types are being compared.

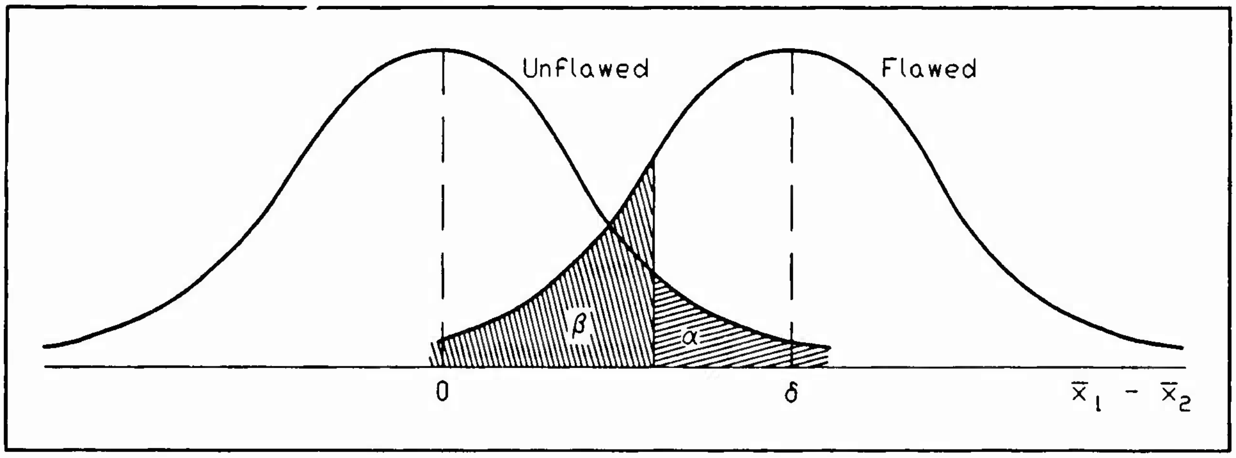

Figure 4-2. Population Distributions

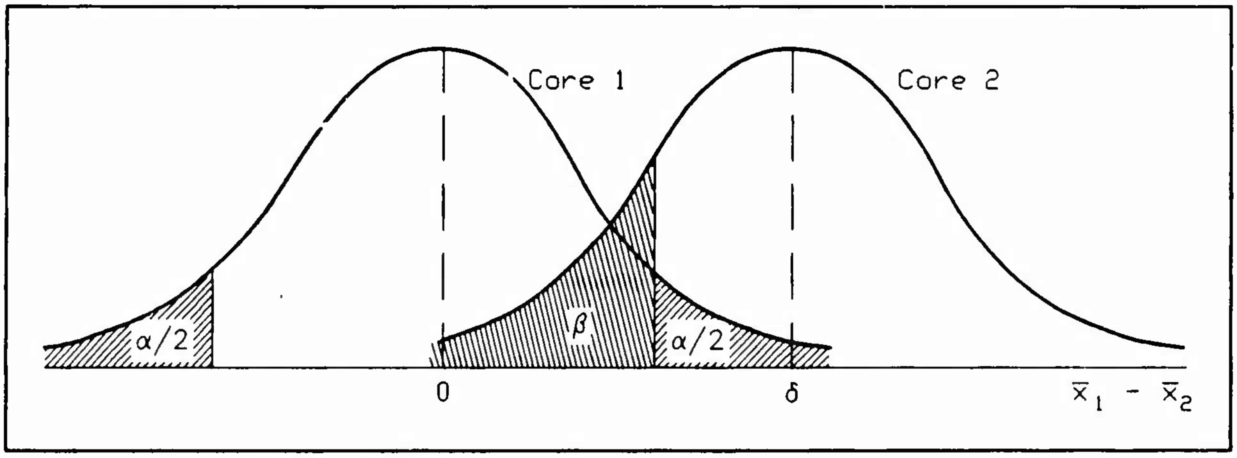

Figure 4-3. Distributions for Two Core Types

For the case shown in **Figure 4-2**, the null hypothesis, H_0, is that the population means for flawed and unflawed coupon breaking strengths are equal. The alternative hypothesis, H_1, is that the flawed coupons have a lower mean breaking strength than unflawed coupons.

$$H_0: \quad \mu_1 = \mu_2$$
$$H_1: \quad \mu_1 > \mu_2$$

For the case shown in **Figure 4-3**, the null hypothesis is that the population means for the core types being compared are equal. The alternative hypothesis is that they are unequal.

$$H_0: \quad \mu_1 = \mu_2$$
$$H_1: \quad \mu_1 \neq \mu_2$$

Rejection of the null hypothesis when it is true is called a **type I error**. Acceptance of the null hypothesis when it is false is called a **type II error**. For any value of $\bar{x}_1 - \bar{x}_2$, there is a probability that we will be making a type I error, α, and a probability that we are making a type II error, β. Statistical tables that show the minimum number of runs needed to differentiate two means that are a distance, δ/σ, apart are available. The desired values of

α and β must be selecte[illegible] [illegible]able 4-2 gives a portion of one such table for the region of interest when comparing flawe[illegible] [illegible]d unflawed samples. **Table 4-3** shows the same information for use in comparing core types. The sample sizes in these tables are the total of all coupons being compared.

Table 4-2. Minimum Sample Size for Single-Sided Test

Type I Error Probability, α = 0.05, (single-sided)				
Distance Between Means $\lvert\delta\rvert/\sigma$	Probability of Making a Type II Error, β			
	0.05	0.10	0.20	0.50
.5	88	70	51	23
.6	61	49	36	16
.75	40	32	23	11
.85	31	25	18	9
1.0	23	18	14	7
1.2	16	13	10	5
1.5	11	9	7	4
2.0	7	6	4	–
3.0	4	3	–	–

Table 4-3. Minimum Sample Size for Double-Sided Test

Type I Error Probability, α = 0.05, (double-sided)				
Distance Between Means $\lvert\delta\rvert/\sigma$	Probability of Making a Type II Error, β			
	0.05	0.10	0.20	0.50
.5	106	86	64	32
.75	48	39	29	15
.85	37	31	23	12
1.0	27	23	17	9
1.1	23	19	14	8
1.3	17	14	11	6
1.5	13	11	9	5
2.0	8	7	6	4
3.0	5	4	4	–

Tables 4-2 and **4-3** assume that the variances of all the samples are equal and pooled. Even though the flawed and unflawed samples may have different sample variances, **Table 4-2** can still be used if the distributions are normal and the size of the flawed and unflawed samples are the same. The resulting errors are small.

Both type I and type II errors should be minimized in this experiment. Type I errors might lead to retaining a flaw or core type for more testing when it could be eliminated as having no effect on the experiment outcome. With a type II error, combinations of flaw or core types might be eliminated when they do cause significant strength effects. Only one value of α is given in **Tables 4-2** and **4-3**. Other values can be found in the literature, but 0.05 is commonly used. It is recommended that β also be chosen as 0.05.

If a sample size of 18 is chosen, from **Table 4-2** we see that we are able to reliably separate differences between flawed and unflawed sample means as small as $1.2 \cdot \sigma$. A sample size of 24 allows separation of means as small as $1 \cdot \sigma$. Either 18 or 24 could be chosen as the pooled sample size. From step 1, we already have a sample size of 24 for each of the solid samples, 12 unflawed and 12 flawed.

Cored samples provide more latitude for pooling sample variances. There are three core types (balsa, Divinycell™, and Airex™) and two flaw levels (unflawed and large flaws). This gives six data points over which to divide the runs. There would be 3 runs at each data point if a sample size of 18 were chosen and 4 if a sample size of 24 were chosen. Although either is reasonable, a sample size of 24 is recommended for consistency with the solid samples. Also, since 24 coupons can be cut from a single panel, all coupons being compared can be laid up together.

All of the data must be used in each comparison to obtain the separation levels given in **Tables 4-2** or **4-3**. That is, we must average the flawed and unflawed test results across core types when making our comparison. If we compare the flawed and unflawed test results for one core type only, the sample size is reduced to 8 and we can only separate differences in the means of $2 \cdot \sigma$.

From **Table 4-3**, with a sample size of 24, we can differentiate means as little as $1.1 \cdot \sigma$ apart if we use all of the data available. This is awkward when we have three core types to compare. Earlier, we assumed that the variance for all core types was the same. Under this assumption, we can accurately compare samples having different sample sizes. We will take advantage of this to improve the estimate of the means.

First, balsa cored coupons will be compared to the pooled results for Divinycell™ and Airex™ coupons. Breaking strengths for flawed and unflawed balsa core coupons will be averaged together and compared to the combined averages of the other two core types. Divinycell™ and Airex™ should have similar properties. Balsa is the most likely core type to show a difference in test results.

If we conclude from this core type comparison that using a balsa core is the same as using the other core types, then we should make the same comparison by taking each of the other core types singly. If the balsa core type has a significantly different mean breaking strength, then the other two cores should be compared to each other. Only 16 data points are available for this comparison. Because of the reduced sample size, we can only differentiate means greater than $1.35 \cdot \sigma$ apart in this comparison. This is the worst case; however, it is still a reasonable level of accuracy.

Four flawed and 4 unflawed coupons must be tested for each of the 27 flaw and core type combinations (only cored coupons are included here). Three different flaw types can be included on one panel. A set of coupons must be produced for tensile tests and another for flexural tests. This gives a total of 432 coupons (8 x 27 x 2), which equates to 18 panels. No additional testing is required for solid coupons. Sample means and variances for all samples must be computed for use in step 4.

4.4 STEP 4

In step 4, we will test the hypothesis that the population mean strength of the flawed coupons equals the population mean strength of the unflawed coupons. We will also test whether the mean strength of one type of core equals the mean strength of other types of cores. If the hypothesis is true between flawed and unflawed samples, then there is no need for further testing of that flaw type/core type combination. However, even if the mean strengths are equal, if step 1 has indicated that the variance is greater for flawed samples of a particular flaw type than for the unflawed samples, then the flaw type should be considered further in step 5. If the hypothesis is true between two core types, then the supporting arguments shall be documented for further consideration by the contracting organization. Note: if the contracting organization has called for the elimination of a core type, document the supporting argument and proceed with eliminating a core type if indicated by test results.

The procedure below assumes that the populations are normal and have equal variance. Slight departures from either the equal variance or normality assumption do not seriously alter the degree of confidence in the test of the hypothesis. If the population variances are considerably different, then we should still obtain reasonable results when the populations are normal, provided the sample size of each is equal.

A pooled t-test is used to compare mean strengths. The test statistic is:

$$t = \frac{\overline{x_1} - \overline{x_2}}{s_p \cdot \sqrt{1/n_1 + 1/n_2}}$$

where the pooled sample variance is

$$s_p^2 = \frac{s_1^2 \cdot (n_1 - 1) + s_2^2 \cdot (n_2 - 1)}{n_1 + n_2 - 2}$$

n_1 and n_2 are the sample sizes at each data point.

Two analyses are required. One analysis looks at differences between flawed and unflawed coupons. The second looks at differences between core types.

Comparing flawed and unflawed coupons will be discussed first. All variables with a subscript of 1 refer to the unflawed coupons. The subscript of 2 refers to flawed coupons. For this case, the null and alternative hypotheses are:

$H_0: \mu_1 = \mu_2$

$H_1: \mu_1 > \mu_2$

For $\alpha = 0.05$ and a single-sided test, the critical value of t is

$t = 1.717.$

For this analysis, $n_1 = n_2 = 12$. For solid samples, there are 12 flawed coupons and 12 unflawed for each flaw type. The same is true for cored samples, but the test results must be averaged across all three core types.

The values of s_1, s_2, $\bar{x}_1$, and $\bar{x}_2$ are calculated from the results of the 24 test runs. These are used to calculate s_p and t. The calculated value of t is then compared to the critical value of t. If the calculated value of t is higher than the critical value, hypothesis H_1 is assumed to be true. Otherwise, the null hypothesis is true, i.e, the population means of flawed and unflawed samples are equal or within about $1 \cdot \sigma$ of one another. The population means of both flawed and unflawed coupons will be set equal to $\bar{x}_1$ in this case.

If we conclude that the flawed and unflawed samples have different mean values, then

μ_1 will be assumed to equal $\bar{x}_1$, and

μ_2 will be assumed to equal $\bar{x}_2$.

When comparing two core types, the null and alternative hypotheses are:

$H_0: \mu_1 = \mu_2$

$H_1: \mu_1 \neq \mu_2.$

For $\alpha = 0.05$ and a double-sided test, the critical values of t are

$t = \pm 2.074$ 22 degrees of freedom

$t = \pm 2.145$ 14 degrees of freedom.

If we are comparing the balsa-cored coupon results to the pooled results for Divinycell™ and Airex™, then $n_1 = 8$, $n_2 = 16$, and the critical t value with 22 degrees of freedom is used. We are using the subscript 1 to refer to balsa core coupons. If we are comparing two foam cores alone, then $n_1 = 8$, $n_2 = 8$, and t has 14 degrees of freedom.

The values of s_1, s_2, $\bar{x}_1$, and $\bar{x}_2$ are calculated from the results of the test runs. These are then used to calculate s_p and t. The calculated value of t is compared to the critical values of t. If the calculated value of t is below the negative critical value of t or above the positive critical value, hypothesis H_1 is assumed to be true. Otherwise, the null hypothesis is true, i.e., the mean strengths of each core type are equal or within the minimum difference in means discussed in step 3.

If we conclude that the core types have different mean values, then

μ_1 will be assumed to equal $\bar{x}_1$, and

μ_2 will be assumed to equal $\bar{x}_2$.

4.5 STEP 5

The previous four steps taken together constitute a screening experiment designed to eliminate any core and flaw type combinations that do not have a significant impact on coupon strength. In step 5, we will test different flaw sizes for all of the core/flaw types that remain after the screening experiment. The goal of this step is to collect enough test data to be able to plot a curve of breaking strength versus flaw size.

The first four steps can be conducted as one experiment. Step 5 should be performed separately after an interval to allow analysis of steps 1 to 4. The conclusions from those steps are needed before beginning step 5. The amount of work required in step 5 is wholly dependent on the previous steps since only the flaw type/core type combinations remaining after steps 1 to 4 are tested in step 5.

We expect the curve of breaking strength versus flaw size will be smooth and decrease gradually as flaw size increases. Testing three flaw sizes plus unflawed coupons should provide enough data to plot the curve of breaking strength for each flaw type/core type combination.

There is no good rule of thumb for how many test runs should be made at each value of flaw size. The variance of the sample means equals

$$\sigma_{\bar{x}}^2 = \frac{\sigma^2}{\sqrt{n}}$$

Step 2 will provide a good estimate of the variance for each flaw type. However, we will not know what that value is until the tests in step 2 have been conducted. Previous tests on unflawed samples indicate that σ is about 5% of the breaking strength. If a sample size of 6 is used, the calculated mean breaking strength will have a standard deviation of about 2% of the actual breaking strength. This seems to be a reasonable level of accuracy for which to try.

A sample size of 6 is also very practical because a total of 24 coupons can be cut from a single panel of material. A sample size of 6 allows 3 flaw sizes and unflawed coupons to be cut from one panel. Little data are lost if one of the six coupons breaks at the wrong location during testing. The five remaining coupons in the sample provide only a slightly less accurate estimate of the population mean.

Estimating the population variance from six data points is less accurate than the estimate of the mean. For a 95% confidence level, the population standard deviation will fall within the following limits:

$$0.62s < \sigma < 2.45s$$

This may or may not provide the accuracy desired. An alternative is to use the variance data computed in step 2.

If the variance data from step 2 is used, the standard deviations should be assumed to vary linearly from the standard deviation of unflawed coupons to that of a large flaw size. A plot of standard deviation versus flaw size can be constructed to determine the standard deviations at intermediate flaw sizes.

The results of this step will include a plot of mean and minimum breaking strengths versus flaw size. The minimum breaking strength will be calculated based on three standard deviations of the largest probable value of σ. That is $3 \cdot 2.45 \cdot s$ ($7.35 \cdot s$) for a sample size of 6. Three standard deviations equals $3 \cdot 1.70 \cdot s$ ($5.1 \cdot s$) if the data from step 2 are used.

Section 5

TEST REPORT

Mechanical properties fall into two broad classes: coupon properties and material properties. **Coupon properties** are those measured directly by the time of testing. These include coupon dimensions, load and deflection at the initial and final failure points, and the load-deflection curve. **Material properties** are calculated from the coupon properties and are intended to be a representation of the basic properties of the material, independent of the coupon configuration and of the testing methods. Material properties include initial and final failure stresses and moduli of elasticity in tension or bending.

For composite materials, calculations of material properties can be misleading. Since the moduli of reinforcing fibers is much higher than that of the matrix material (polyester resin in this case), virtually all of the tensile or bending loads are carried by the fiber reinforcement. For the coupons used in these tests, the amount of fiber reinforcement per unit coupon width is very tightly controlled by specifying a particular laminate stacking sequence. However, the thickness of the coupons can vary with local or overall variations in the fiber/matrix ratio (the resin ratio). The thickness enters into all material property calculations, often to higher powers in the case of flexural properties.

Tensile breaking loads for coupons having a standard stacking sequence are dependent only upon the coupon width. However, since the calculated material properties are calculated on the actual thickness and cross-sectional area, they will vary with the thickness. This will possibly lead to the misleading conclusions that a thicker coupon is actually weaker when in terms of absolute breaking strength it is not weaker, only heavier. Therefore, for tension, a breaking stress calculated on a cross-sectional area based upon the actual width and upon a standard or nominal thickness is likely to be more meaningful than properties calculated on the actual cross-sectional area, and this is recommended as the property to be used in comparing coupons.

In flexure, the section modulus, moment of inertia, and cross-sectional area depend upon various powers of the thickness and thus vary with the resin ratio for a fixed amount of reinforcement. Flexural breaking loads *will* vary with thickness variations caused by resin ratio variations since moment of inertia affects the bending stiffness. However, stiffness variations due to resin-ratio related thickness variations are not the same as those due to thickness variations in which the amount of fiber reinforcement in the coupon is a linear function of the thickness. Therefore, for flexure, misleading conclusions are possible whether the properties are calculated on actual or nominal thickness. For the purposes of these experiments, the breaking load divided by actual coupon width is considered to be the most meaningful property for comparisons between coupons.

5.1 CALCULATIONS OF MECHANICAL PROPERTIES

For each tensile coupon, the breaking stress in lbf/in^2 will be calculated from data recorded on the Specimen Data Sheet:

$$s = \frac{P}{b_{avg} \cdot (H-h)}$$

where:

s is the breaking stress.

b_{avg} is the average coupon width, which is calculated as specified in the Test Procedure.

h is the core thickness.

H is either the average thickness of the coupon, calculated as specified in the Test Procedure, or the nominal thickness (.5" for solid coupons and .625" for cored coupons).

For each flexural coupon, the failure stress will be calculated from data recorded on the Flexural Specimen Data Sheet:

$$s = \frac{M}{\left[\frac{I}{c}\right]}$$

where:

s is the maximum fiber stress at failure.

M is the maximum bending moment, which occurs over the area between the loading noses, and is $0.1875 \cdot P \cdot L$ where P is the maximum load and L is 20 inches, the support span.

I/c is the section modulus of the coupon and is calculated by:

$$\frac{I}{c} = \frac{b_{avg}}{6} \cdot \frac{(H^3-h^3)}{H}$$

The expression for stress simplifies to:

$$s = \frac{1.125 \cdot P \cdot L \cdot H}{b_{avg} \cdot (H^3-h^3)}$$

The large deflections at failure expected for solid coupons cause significant horizontal components in the support reaction forces, which lower the bending moment in and thus the vertical deflection of the coupon for a given applied load. This reduces the calculated value of stress for a given applied load. Thus, *for solid coupons only*, the following relation should be used for calculating the breaking stress:

$$s = \frac{1.125 \cdot P \cdot L}{b_{avg} \cdot H^3} \cdot \left[1 + 5.3 \cdot \left[\frac{D}{L} \right]^2 - 6.1 \cdot \frac{D \cdot H}{L^2} \right]$$

The correction factor in the right parentheses will result in an increase of approximately 3.5% in the computed stress, counteracting the apparent reduction due horizontal reaction forces at the supports during large deflections.

The calculated breaking stresses or failure stresses for each coupon will be recorded for inclusion in the report and for use in subsequent statistical analysis.

Calculation of tensile moduli and flexural moduli are required by the reporting requirements of ASTM D-3039 and ASTM D-790, respectively. For composite materials, the techniques generally used to calculate these values are not generally considered to result in good estimates of the actual properties.

TENSILE MODULUS

The tensile modulus, if required, is to be calculated as follows:

$$E_t = \frac{m_t}{b_{avg} \cdot (H - h)}$$

where:

m_t is the slope of the plot of load vs. strain in the linear portion of the curve.

H is the average total thickness of the coupon, or, alternatively, the nominal thickness.

h is the core thickness, where applicable.

FLEXURAL MODULUS

The flexural modulus, if required, is to be calculated as follows:

$$E_b = \frac{0.229 \cdot m_b \cdot L^3}{b_{avg} \cdot (H^3 - h^3)}$$

where:

m_b is the slope of the load vs. deflection curve in the linear portion.

h is the core thickness, where applicable.

H is the average total thickness of the coupon, or, alternatively, the nominal thickness.

Note that this expression differs from those presented in ASTM D-790 because the load arrangement specified for this project uses a load span of 1/4 the support span, as opposed to the centered load of Method I and load spans of 1/3 and 1/2 the support span of Method II specified by the ASTM standard. The derivation of the bending moment equation and of the flexural modulus expression above is presented in Appendix A of this Test Plan.

5.2 REPORTING REQUIREMENTS

The format of all reports will be in accordance with DOT Order 1700.18B. All numerical results will be reported in U.S. Customary Units.

The following paragraphs designate items that will be included in the test report.

5.2.1 GENERAL REPORTING. The report will contain a synopsis of the important features of each experiment, including the purpose of the particular experiment (i.e., "comparison of mean flexural strengths of Airex™ cored coupons with and without voids"), the number of coupons tested, and the various flaw types and core types involved in the experiment.

There will be a detailed report of the materials, techniques, and conditions of coupon fabrication, including all the applicable information required by paragraph 11 of ASTM D-3039 and paragraph 12 of ASTM D-790. There will also be a general report of testing procedures, including the applicable information required by paragraph 11 of ASTM D-3039 and paragraph 12 of ASTM D-790.

The report will contain the conditioning procedures, including information required by paragraphs 8 and 11 of ASTM D-3039 and paragraphs 8 and 12 of ASTM D-790 and photographs taken to document the testing, with suitable captions and explanations.

The report will also include comparisons of the properties of similar laminate panels from which the test coupons were cut including mean strengths, which will be calculated from the measured strengths of all the unflawed coupons in each panel, and glass/resin ratio and void content. The tests for resin and void content are specified in the Test Procedure. These comparisons are made in order to evaluate the consistency of the coupon fabrication techniques.

5.2.2 COUPON DATA REPORTING. The report will contain a copy of each Specimen Data Sheet (tab failures are reported here for tensile coupons).

The report will contain the results of the strength calculations detailed in paragraph 5.1.

The report will contain the applicable information required by paragraph 11 of ASTM D-3039 for tensile coupons and by paragraph 12 of ASTM D-790 for flexural coupons.

The report will also contain sample means, variances, and ratios of variances that were computed. The highest possible population variance ratio will be computed per paragraph 4.2 and reported. Values of the t statistic computed per paragraph 4.4 will also be reported.

5.2.3 CONCLUSIONS. The report will contain the conclusions reached in each part of Steps 1-4 of this Test Plan with regard to the equality or inequality of mean strengths and strength variances for coupons having various flaw and core types. All conclusions will be reported with corresponding confidence levels.

The report will include the design for the step 5 experiments, which is contingent upon the conclusions of the experiments in steps 1-4. (As a result of steps 1-4, certain flaw types and/or core types can be excluded from the experiments in step 5).

The report will detail the conclusions reached in the experiments in step 5. The report will include all conclusions about the effects of flaw type and flaw size on the strength of test coupons, and these conclusions will be supported by graphical presentations showing the relationship of strength to flaw size for all combinations of flaw types and core types tested, in step 5, for both tensile and flexural tests. Confidence levels will be reported for all conclusions.

5.2.4 RECOMMENDATIONS. Recommendations will be included concerning the interpretation of the results that are presented.

Recommendations will be included regarding the need for further experimentation and whether changes in coupon dimensions, fabrication techniques, test procedures, or experiment design would be desirable in further experiments.

APPENDIX A Calculation of Flexural Modulus for Non-Standard Load Spans

While a number of sources indicate that flexure tests based upon ASTM D-790 are not a reliable source of information about the flexural modulus of composite materials, calculations of flexural moduli may be required under some circumstances.

ASTM D-790 gives formulas for calculation of flexural modulus for the three-point bending test (Method I - a single centered load) and for two versions of the four-point test (Method II - two load points) using load spans of one-half and one-third the support span. **Figure 3** shows the specified Flexural Test Setup: a load span of 5" over a support span of 20". Formulae for calculation of flexural modulus for a load span of one-quarter the support span are not given in ASTM D-790. The appropriate formula is derived here; the same method can be followed to derive the formula for any other nonstandard load span/support span ratio.

The general equation for the elastic bending of a beam (Roark and Young 1982) is:

$$EI\frac{d^2y}{dx^2} = M$$

where: M is the equation for bending moment at a given position x, measured from the left end of the beam.

For a simply supported beam, integration of this expression leads to:

$$y = \int_0^x \frac{Mx}{EI}\,dx$$

where: y is the vertical deflection of the beam, measured at x,
M is the bending moment equation, as above, and
x is measured from the left support

For a load equal to 1/4 the support span, the bending moment equation is:

$$M = \left(\frac{P}{2}\right)x - \left(\frac{P}{2}\right)\left\langle x - \frac{3}{8}L\right\rangle$$

which results in a constant bending moment of 3/16$\cdot$P$\cdot$L over the load span. The brackets $< >$ indicate a step function, i.e., a function that takes the value of the expression inside the brackets when that expression is positive but which takes a value of zero when that expression is negative.

For a symmetrically-loaded beam, the maximum deflection occurs at the center of the support span. Integrating stepwise out to the center of the span:

$$y = \int_0^{.375L} \left(\frac{Px}{2}\right) x\,dx + \int_{.375L}^{.5L} \left(\frac{3PL}{16}\right) x\,dx$$

Evaluating the integrals:

$$y = \left.\frac{Px^3}{6}\right|_0^{.375L} + \left.\frac{.1875PL}{2}x^2\right|_{.375L}^{.5L}$$

This expression evaluates to:

$$y = \frac{0.01904PL^3}{EI}$$

where: $$I = \frac{b(H^3-h^3)}{12}$$

H is the beam depth and h is the core thickness (if applicable)

The core material is assumed not to carry any bending stresses, thus the sectional properties (section modulus and moment of inertia) of cored beams are calculated on cross-sections of the laminate skins only, with the core's only function being maintaining a constant separation of the skins. This assumption is in accordance with the general practice for analysis of flexure of sandwich constructions (Whitney 1973).

The flexural or bending modulus E_b is calculated by substituting the value of the moment of inertia into the above equation and rearranging:

$$E_b = \frac{0.2285L^3P}{b(H^3-h^3)y}$$

If the slope of the tangent to the load/deflection (P/y) curve at the zero-load point is denoted as m, the flexural modulus is calculated as:

$$E_b = \frac{0.2285L^3m}{b(H^3-h^3)}$$

for a load span of 1/4 the support span.

The procedure detailed above gives similar results for any load span, with the constant term in the numerator of the last equation being the only varying parameter. Values of this constant term obtained by this method yield the following values for the constant term:

Centered Load:	0.25
Load span 1/4 the support span:	0.2285
Load span 1/3 the support span:	0.2129
Load span 1/2 the support span:	0.1719

ASTM D-790 uses the following values:

Centered Load:	0.25
Load span 1/4 the support span:	not given
Load span 1/3 the support span:	0.21
Load span 1/2 the support span:	0.17

This procedure can be used, with appropriate substitutions of the correct bending moment equation, to calculate the flexural modulus of a simply supported beam with any symmetrical loading arrangement.